



Risk Assessment and Capacity
Development in Costa Rica

Probabilistic Risk Assessment of Buildings and Infrastructure in the Canton of Heredia

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Prepared for:



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Risk Assessment and Capacity Development in Costa Rica

Probabilistic Risk Assessment of Buildings and
Infrastructure in the Canton of Heredia.

Product 6

(Deliverables: 5b, 5c, 5d)

Prepared for:



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Consultant team

INGENIAR CAD/CAE Ltda.
Carrera 19A # 84-14 OF 504
Edificio Torrenova
Bogotá, D.C., Colombia
www.ingeniar-risk.com



Centro Internacional de Métodos
Numéricos en Ingeniería
Edifici C1 Campus Nord UPC
C/ Gran Capità, S/N 08034
Barcelona, España
www.cimne.com



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1 INTRODUCTION

The Global Risk Modelling Alliance (GRMA), supported by the InsuResilience Solutions Fund (ISF), aims to strengthen the capacity of countries and cities to conduct climate and disaster risk analyses with a focus on financial decision-making. The initiative seeks to fill critical gaps in modelling and data, thereby enhancing climate and disaster risk assessments at both national and sub-national levels.

To achieve this goal, the GRMA works closely with local partners to identify and jointly define each country's specific needs, providing open-access risk management tools, data resources, and operational expertise in risk financing.

In Costa Rica, the GRMA has established a collaboration with the government—through its institutions under the leadership of SUGESE—to strengthen national capacities for climate risk management. This partnership will deliver relevant models and analytical tools to inform the country's national strategies for risk financing and disaster risk mitigation.

The program is being implemented in phases, beginning with the assessment of specific needs and culminating in the integration of advanced risk-modelling tools into public policy frameworks.

The project is funded by Germany's KfW Development Bank and administered by Frankfurt School on behalf of the GRMA.

The INGENIAR–CIMNE Consortium was selected to provide risk modelling services within the framework of the collaboration between the GRMA and the Government of Costa Rica, through an application focused on four risk assessment projects:

- Strategic Project: Demonstration of risk assessment methodologies for critical infrastructure in Heredia.
- Operational Project 1: Disaster and climate risk assessment for road infrastructure – National Route 2 (RN2), Pan-American Highway.
- Operational Project 2: Flood and drought risk analysis for small and medium-sized agricultural producers.
- Operational Project 3: Exposure and risk assessment for small and medium-sized hotels and lodges participating in the Fu-turismo program.

Implementation is carried out through the CAPRA-ROBOT modelling platform, developed by INGENIAR, which will also serve as an educational tool within the Training Program that runs throughout the entire duration of the consultancy.

This report corresponds to Product 6 “*Probabilistic Risk Estimation for Buildings and Infrastructure in the Canton of Heredia*”, specifically addresses Deliverables: 5b “Probabilistic estimates of fluvial and pluvial flood and earthquake risk in Heredia”, 5c “Technical report on developed or improved model/data/methodology and replicability”, and 5d “Documentation of capability development, activities undertaken, participation, and feedback” of the Terms of Reference of this consultancy. It is therefore a product exclusively related to the Strategic Project.

This report presents the results of the probabilistic risk assessment for buildings and critical infrastructure in the canton of Heredia, considering the following hazards: earthquakes, riverine flooding, pluvial flooding, and landslides, the latter three influenced by climate change. This assessment builds upon and complements aspects previously presented in earlier products: (i) Product 2 “Review geohazard data and proposal on applying in risk assessment” presents the pre-existing seismic hazard and landslide susceptibility models used in this evaluation; (ii) Product 3 “Exposure and Vulnerability Models” of this consultancy contains the details of the exposure model for buildings and critical infrastructure in Heredia, composed of multiple subsectors, as well as the vulnerability functions applied to these portfolios; and (iii) Product 4 “Climate Hazard Models” contains the details of the climate hazard models developed for riverine and pluvial flooding, including the high-resolution riverine flood model developed specifically for Heredia.

1.1 Scope of the Strategic Project

The objective of this Strategic Project is to conduct multi-sector infrastructure risk modeling in the canton of Heredia.¹ This project involves the assessment of seismic, flood, and landslide risk (triggered by earthquakes and intense rainfall) for the portfolio of buildings and infrastructure in Heredia, based on the information made available by the canton.

The project is implemented through the activities presented in Table 1. The corresponding schedule is shown in Figure 1. All aggregated values presented were agreed upon directly with the Technical Working Group (TWG) of this project.

Table 1. Tasks of the Strategic Project

Activity	Description	Task in the ToR	Deliverable in the ToR
Climate model	Refers to the modeling of meteorological forcing and the incorporation of climate change projections.	T2.1, T2.2	D2.1a–f, D2.2a–e
Pirro River flood model	A detailed flood model is developed for the Pirro, Bermúdez, Burío rivers and Quebrada Seca, to be used as a hazard input for the canton of Heredia.	T2.1	D2.1a–f
Seismic hazard model	The best available national seismic hazard model is selected, allowing its direct application in catastrophe modeling.	T3.3	D3.3a–b
Heredia site effects	An information layer of site effects is generated to approximately represent soil response within the canton, in order to obtain improved results in seismic risk assessment.	<i>Added value</i>	—
Landslide hazard model	A landslide susceptibility and hazard model is developed at the scale of the canton of Heredia.	<i>Added value</i>	—
Heredia building exposure	An exposure layer at the level of individual buildings within the canton is constructed, characterized by height, use, socioeconomic level, structural system, replacement cost, among other relevant attributes.	T5.1, T5.2	D5a
Infrastructure exposure	An exposure database for infrastructure is developed across multiple sectors (e.g., roads, water and sanitation, energy).	T5.1, T5.2	D5a
Building vulnerability	Refers to the definition of vulnerability curves for buildings in Heredia.	T4.1, T5.3	D4a–d
Infrastructure vulnerability	Refers to the development of vulnerability curves through an archetype model of infrastructure elements.	T4.1, T5.3	D4a–d

¹ Refers to existing critical infrastructure in the canton, in accordance with the definitions established in Decree No. 42465 of MOPT-MINAE-MIVAH.

Activity	Description	Task in the ToR	Deliverable in the ToR
Risk assessment	Application of the methodologies presented here to evaluate risk using actuarial metrics from catastrophe modeling.	T5.4	D5b–c
Result calibration	The analytical loss exceedance curve calculated with the model is compared with one constructed from historical event data to assess their correspondence.	T5.4	D5b–c
Investment curve	As a value-added component, a set of risk management actions will be evaluated to determine the optimal combination for risk reduction under fixed and increasing investment levels.	<i>Added value</i>	—
Resilience assessment	The resilience of the canton will be evaluated by incorporating its capacities to absorb, respond, and recover, in order to obtain a resilience metric for its infrastructure.	<i>Added value</i>	—

Task	15 Jan 2025		Month												15 Apr 26	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Strategic Project: Demonstration of Risk Analysis Methods for Critical Infrastructure in Heredia																
Climate model																
Pirro River flood model																
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Heredia site effects																
Landslide hazard model																
Heredia building exposure																
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Building vulnerability																
Infrastructure vulnerability																
Risk assessment																
Result calibration																
Investment curve																
Resilience assessment																

Figure 1. Schedule of activities for the Strategic Project. (Blue cells indicate implementation. Green cells indicate product delivery. Red cells correspond to this product 6)

2 CATASTROPHE RISK MODELING METHODOLOGY

The objective of probabilistic catastrophic risk modeling is to estimate the probability distribution of losses that may occur within a set of exposed elements, following the occurrence of a hazard event (Cardona, 1986a;b;c; 1989; 1990, Bernal et al., 2021). Probabilistic modeling enables forecasting of future loss levels by accounting for the specific hazards present in the territory and the inherent uncertainties in their estimation, as well as the intrinsic vulnerability of the exposed elements and its respective uncertainty.

2.1 Conceptual Approach to Risk Modeling

Probabilistic risk modeling involves estimating the potential consequences that a set of exposed elements may suffer as a result of hazardous events. Robust risk modeling is fundamental for building a sustainable and resilient development process, as it enables the consideration of trade-offs between potential harms and benefits. In other words, such a process can only be effectively guided when supported by a risk model that is sufficiently robust, both in terms of credible impact estimations and in providing a sound technical foundation for decision-making without arbitrariness.

The general procedure for probabilistic disaster risk modeling—considering climate change—is illustrated in Figure 2

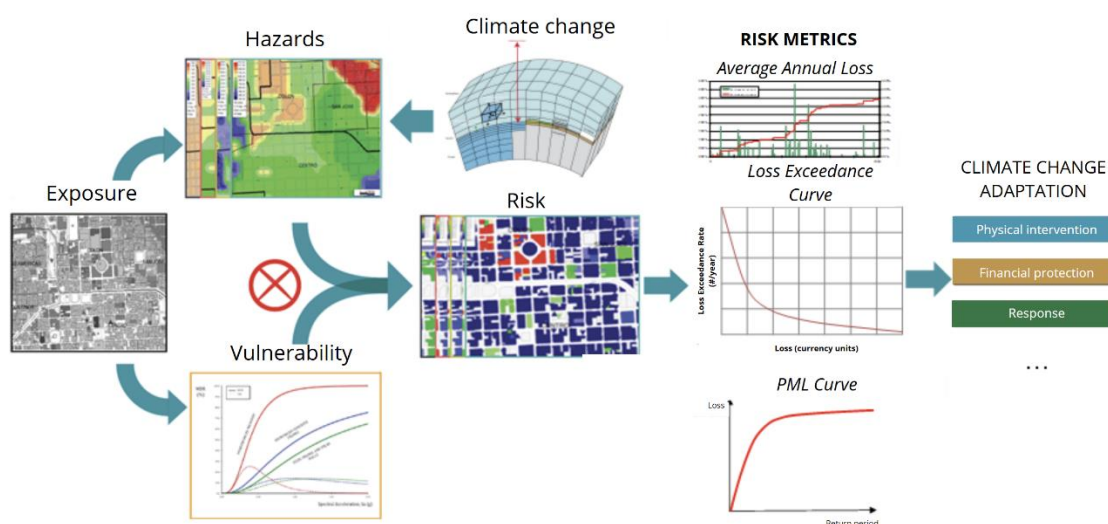


Figure 2. Components of Risk Modeling and Their Interrelation.

As illustrated in Figure 2, once risk has been evaluated using actuarial metrics, such as Expected Annual Loss, the Loss Exceedance Curve, and Probable Maximum Loss, it becomes possible to establish an objective relationship with risk management measures and their effectiveness. This means the model can be used to design intervention strategies composed of multiple measures, each with a quantifiable capacity to reduce risk.

Following this approach, risk in this study is evaluated based on three fundamental factors:

- *Hazard* is defined as a set of stochastically simulated events that are collectively exhaustive and mutually exclusive; that is, they cover all possible ways in which the hazard may manifest,

assuming independent events whose frequencies follow a natural power law (i.e., equivalent to a recurrence curve).

- *Exposed elements* refer to immovable assets, infrastructure, or agricultural production that are subject to hazards and susceptible to damage or disruption.
- *Vulnerability* refers to the propensity or predisposition of exposed elements to be adversely affected. Assessing vulnerability requires a specific model for each type of exposed element and each type of hazard—there is no unified representation. However, the modeling process results in a common impact metric (economic loss), which makes the different models additive and comparable in risk terms.

The first fully probabilistic approach to the risk problem from an actuarial perspective was proposed by Filip Lundberg in 1903 (Lundberg, 1903). In 1930, Harald Cramér formalized Lundberg’s theory into what is now known as Ruin Theory (Cramér, 1930). Lundberg defined an income-outcome model in which an insurance company begins operations with a given amount of capital, which increases over time as premiums are collected. Simultaneously, losses (which the company must cover) occur randomly over time. If, due to claim payments, the company’s capital falls below zero, it is considered bankrupt. Lundberg was interested in determining the probability of an insurance company’s insolvency.

Ruin Theory assumes that the occurrence of claims is not deterministic. Lundberg demonstrated that the occurrence of losses over time can be modeled as a Poisson process. Later, it was shown that any renewal process is valid within the framework of Ruin Theory (Andersen, 1957). A renewal process is a type of continuous-time, discrete-state stochastic process widely used across scientific and engineering disciplines to model the random occurrence of events. In this context, “events” refer to loss occurrences, regardless of their origin. This is why Ruin Theory—or insolvency theory—is well-suited to modeling the impacts associated with any type of phenomenon, whether natural or not, and is applicable to risk management beyond the insurance sector, including social, economic, environmental, and broader development contexts.

A renewal process is defined by a single parameter: its intensity or rate. In risk assessment, this parameter corresponds to the loss exceedance rate, which is the inverse of the average time between events that exceed a given loss threshold p . Therefore, when estimating the risk of a portfolio of exposed elements (i.e., the probability of exceeding a loss amount p within a time window), its exceedance rate $v(p)$ must be calculated based on the probability of occurrence of any hazard event capable of surpassing p . This defines a renewal process that enables estimation of the probability of loss p being exceeded within any given period.

2.2 Risk Quantification

From a mathematical standpoint, risk modeling aims to characterize a stochastic process of loss occurrence over time (i.e., a loss process). A loss process has key characteristics that shape the modeling approach adopted in this study, which is commonly used in actuarial catastrophic modeling, safety and reliability engineering, the aerospace industry, and other fields.

Risk is determined by the convolution of hazard and vulnerability, at the location of the exposed elements and for all such elements. In probabilistic loss modeling, both hazard and vulnerability are represented probabilistically. Hazard is characterized by both temporal and spatial probability distributions. The temporal occurrence of hazard scenarios is modeled as a renewal process, which entails fitting a probability model to the time between two consecutive events.

The uncertainties associated with hazard and vulnerability are defined by their own nature—temporal and spatial for hazard, and intensity-dependent for vulnerability. As such, the primary output of the model is a specific probability distribution of loss for each hazard event. The probability density function of loss for exposed element j , conditional on the occurrence of hazard event i (i.e., $f(p_j|E_i)$), is calculated as:

$$f(p_j|E_i) = \int_0^{\infty} f(p_j|s)f(s|E_i)ds \quad \text{Equation 1}$$

where the first term of the integral pertains to vulnerability ($f(p_j|s)$, the probability density of loss given an intensity s), and the second term relates to hazard ($f(s|E_i)$, the probability density of intensity given the occurrence of event E_i).

The total loss from event i is the sum of all individual losses (p_j) from the exposed elements. Since these are random variables, proper arithmetic must be used to determine the total event loss. The sum is computed over the probability moments of the variables p_j , as follows:

$$E(p|E_i) = \sum_{j=1}^{NE} E(p_j) \quad \text{Equation 2}$$

$$\sigma^2(p|E_i) = \sum_{j=1}^{NE} \sigma^2(p_j) + 2 \sum_{k=1}^{NE-1} \sum_{j=2}^{NE} cov(p_k, p_j) \quad \text{Equation 3}$$

where $E(p|E_i)$ is the expected loss of event i , $\sigma^2(p|E_i)$ is its variance, NE is the total number of exposed elements, $E(p_j)$ is the expected loss for element j , $\sigma^2(p_j)$ is its variance, and $cov(p_k, p_j)$ is the covariance between losses in two different exposed elements.

Using the probability moments of the total loss from an event, a Beta distribution is fitted, with the following probability density function (f_p):

$$v(p) = \sum_{i=1}^N Pr(P > p|E_i) \cdot F_A(E_i) \quad \text{Equation 4}$$

where $v(p)$ is the exceedance rate for loss p , N is the total number of hazard events, $F_A(E_i)$ is the annual frequency of event i , and $Pr(P > p|E_i)$ is the probability of exceeding p given that event i occurred. The summation includes all hazard events that can generate losses. The inverse of $v(p)$ is the return period of loss p (Tr), which is simply the expected time between events that exceed loss p .

$$Tr = \frac{1}{v(p)}$$

Equation 5

The loss exceedance curve contains all the necessary information to probabilistically characterize the loss occurrence process associated with hazard events. Figure 3 shows an example of a loss exceedance curve.

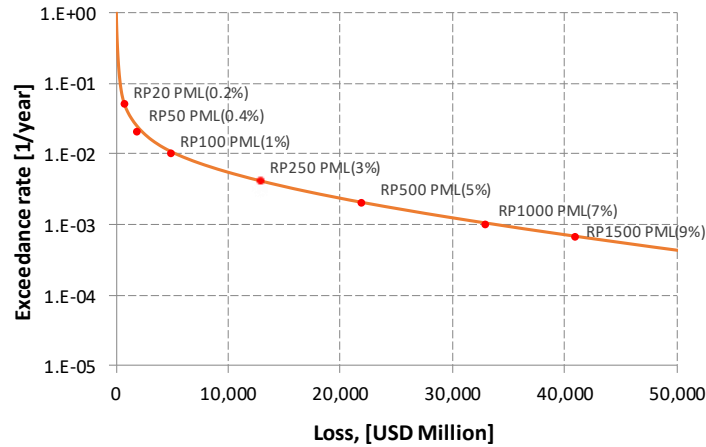


Figure 3. Example of a loss exceedance curve. The vertical axis shows the exceedance rate. The horizontal axis shows the associated loss. (RP = Return Period; PML = Probable Maximum Loss).

The calculation in Equation 4 corresponds to the estimation of the exceedance rate for all loss amounts across all exposed elements, for all events in the hazard model, and for all hazards. As shown in Figure 4, the probabilistic risk assessment can be summarized in the following steps: 1) For each hazard event, the loss for every exposed element is determined; 2) the total event loss is calculated as the sum of individual losses; 3) once all event losses are quantified, exceedance rates are calculated.

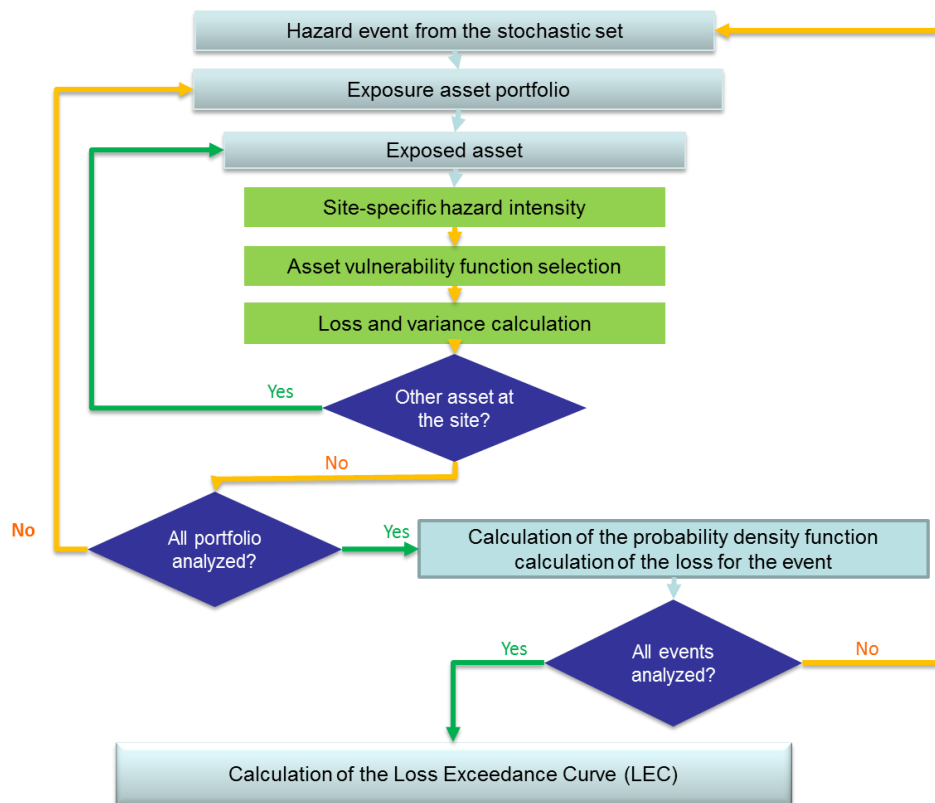


Figure 4. Flow diagram of probabilistic risk assessment

2.3 Risk Metrics

From the loss exceedance curve, several risk metrics can be derived, each serving different purposes in decision-making and risk management processes. These metrics offer a comprehensive representation of risk, typically condensed into one or a few indicators, rather than presenting the full set of event-specific losses or the entire exceedance curve.

2.3.1 Average Annual Loss (AAL)

The AAL represents the expected value of annual losses. It reflects the average annual amount which, when accumulated over time, would be equivalent to all future losses. Conceptually, the AAL corresponds to the fair pure premium required annually to cover all possible losses. It can be calculated as the area under the loss exceedance curve:

$$PAE = \int_0^{\infty} v(p) dp \quad \text{Equation 6}$$

Alternatively, based on event-specific loss data, AAL can also be calculated as:

$$PAE = \sum_{i=1}^N E(P|E_i) F_A(E_i)$$

Equation 7

Where $(P|E_i)$ is the expected loss from event i , and $F_A(E_i)$ is the annual frequency of occurrence of event i . The expected loss given the occurrence of a specific event depends on the vulnerability of the exposed elements.

AAL is a crucial risk indicator because it integrates into a single value the impact of hazardous events on vulnerable exposed elements. It is the most robust risk metric—not only because it summarizes the loss occurrence process in one number, but also because it is relatively insensitive to uncertainty, as it reflects the mathematical expectation of annualized losses.

2.3.2 Probable Maximum Loss (PML)

While the loss exceedance curve is the primary output of risk assessment, the PML curve is often preferred, as the concept of a return period is generally easier to interpret. As previously explained, the return period is the expected time between events that exceed a certain loss, and it is mathematically the inverse of the exceedance rate. The loss exceedance curve and the PML curve contain equivalent information.

From the PML curve, loss values can be determined for any selected return period. Choosing a return period to reference a PML value depends entirely on the risk aversion of the decision-maker. Figure 5 shows an example of a PML curve, where a selected return period of 400 years on the horizontal axis corresponds to a loss value on the vertical axis. This indicates that such a loss is expected to be exceeded, on average, once every 400 years.

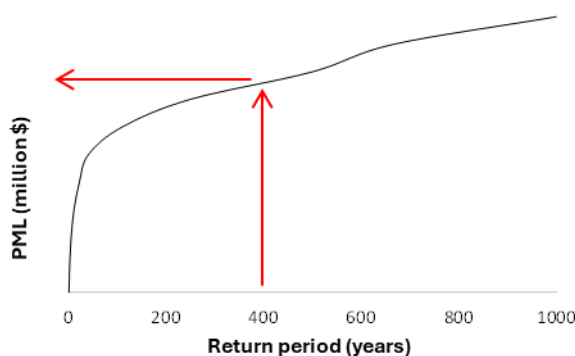


Figure 5. Example of a PML curve

2.4 Limitations of the Risk Assessment in Heredia

This section presents several widely recognized limitations of probabilistic risk assessment, which are strongly related to the quality of the available data. It should be noted that the limitations described here complement those previously indicated in all products of this consultancy, which addressed the assessment methodology (Inception Report), information on pre-existing geological hazard models (Product 2 “Review geohazard data and proposal on applying in risk assessment”), the exposure and vulnerability models developed in this consultancy (Product 3 “Exposure and Vulnerability Models”), and the hydrometeorological hazard models with climate change developed by the consultant (Product 4 “Climate Hazard Models”).

Therefore, this section does not seek to repeat what has already been stated in those previously submitted products, but rather to provide a general overview of the known limitations of probabilistic risk assessment.

Probabilistic disaster risk assessment critically depends on the availability and resolution of the information used to model hazards, exposure, and vulnerability. A common limitation is the insufficiency of historical records of extreme events, which makes it necessary to simulate the largest and most catastrophic events based on indirect information about the territory and the manifestation of the phenomena.

This prevents strict calibration and validation processes, since there is no evidence of the occurrence of most of the simulated events, as they have not yet occurred. This is particularly true under climate change conditions. Likewise, in modeling climate-related phenomena, hydrometeorological data often present temporal gaps, low spatial density of monitoring stations, or inconsistencies due to changes in measurement systems.

Table 2 summarizes the main limitations of the different modeling components—hazard, exposure, and vulnerability—and also provides some recommendations for their reduction.

Table 2. Summary of identified limitations in the model components.

Layer	Condition Evaluated	Limitation	Recommendation
Climate	Baseline climate and 36 future climate scenarios	It is not possible to anticipate the actual future climate. Only possible alternative futures can be considered and evaluated.	Deep uncertainty. It cannot be reduced.
Flood hazard	Meteorological forcing. Daily-scale simulations	Simulations were obtained for 1,000 years at locations within a grid of points over Costa Rica. This grid has low resolution at the scale of the canton of Heredia, meaning that spatial variations in rainfall patterns cannot be fully captured by the model.	Requires investments in research, detection equipment, and long-term data collection.
Flood hazard	Basin response	The basin response model captures internal spatial variations that modify local attenuation and accumulation conditions through surface infiltration. However, the basins considered are highly intervened and transformed, with urban drainage routes not included in the model that alter response patterns. Minimal or absent maintenance of basins and channels	Requires investments in research and river/channel monitoring.

Layer	Condition Evaluated	Limitation	Recommendation
		also affects the ability to properly represent hydrological response.	
Flood hazard	Hydraulic model	Two-dimensional hydraulic model, appropriate for river overflow flooding, mainly in inundated areas. Model response within the channel, especially in deeper channels, is uncertain due to its two-dimensional nature. It is not appropriate for more intense phenomena such as torrential flows, as it does not include sediment loads from basin materials or solids generated by human activity (waste and debris) that modify the rheology of the flowing fluid.	Requires investments in research.
Seismic hazard	Earthquake occurrence. Strong ground motion	Seismic information is limited due to the relatively low frequency of earthquakes. Seismic hazard models must always be treated probabilistically because of uncertainties in timing, location, magnitude, and other event characteristics.	Requires time and significant investment in research.
Seismic hazard	Site effects	Site effects are fundamental for accurately evaluating surface ground motion experienced by exposed elements. The model proposed for Heredia is highly approximate. More specialized geotechnical and geophysical information is required, as well as microzonation models to properly capture site effects.	Requires major investments in subsurface research.
Landslide hazard	Susceptibility	The susceptibility model was derived from a global model (GIRI-CDRI) and downscaled through assignment based on topographic slope. This is a highly approximate and coarse condition, as it does not consider geotechnical material properties, land use conditions, or other susceptibility factors.	Requires major investments in subsurface research and susceptibility modeling.
Exposure	Building exposure	The canton of Heredia has very good information on exposed elements, with access mainly to cadastral data for this exposure portfolio. Costa Rica also has official documents for the economic value of real estate. However, the information must be processed to transform it into an exposure database.	Requires investment in generating and maintaining exposure information, not only cadastral data.
Exposure	Infrastructure exposure	The canton of Heredia has very good information on exposed elements, with multiple sources providing mainly location data and, to a lesser extent, other attributes (size, capacity, value). Although the available information is of good quality, it must be processed to create a proper exposure database.	Requires investment in generating and maintaining exposure information beyond location data for the elements.
Vulnerability	Building vulnerability	Vulnerability functions previously applied in projects in Costa Rica (e.g., GRAF, CAPRA) are available. Although they are not country-specific curves, they are considered acceptable. New functions had to be developed for certain sectors (e.g., health), using an archetype model that considers building contents. Validation of new vulnerability functions is analytically and technically complex and computationally demanding.	Requires investment in vulnerability model research.
Vulnerability	Infrastructure vulnerability	In some cases, vulnerability functions for infrastructure elements (e.g., HAZUS) were adopted, while in others new functions were created using an archetype approach. These functions are considered sufficient for the purposes of the assessment. However, validating new vulnerability functions is analytically complex and	Requires investment in vulnerability model research.

Layer	Condition Evaluated	Limitation	Recommendation
		computationally demanding. Additionally, the model only considers direct losses to infrastructure elements and does not account for service disruptions in networked systems (e.g., road networks, power networks, water supply systems), nor the interdependence among these systems.	

Although Costa Rica stands out in the region for having solid and well-structured information systems as inputs for modeling, inherent limitations of the probabilistic approach remain. The main challenge lies in the fact that modeling is based on the projection of future events that have not yet occurred, which implies reliance on analytical assumptions regarding the extreme behavior of natural hazards and the response of exposed elements to them. Therefore, even in contexts with good data availability, such as Costa Rica, uncertainty cannot be completely eliminated; it can only be explicitly managed within the risk assessment process.

2.5 Recommendations for Future Assessments

Based on the inherent limitations of the assessment, several general recommendations are proposed to strengthen the future use of probabilistic risk assessment models:

1. Institutional use of results as the official risk baseline

It is recommended that local institutions adopt the portfolio-level AAL and PML results, as well as element-level risk metrics, as the official baseline for characterizing multi-hazard risk in the canton of Heredia. These results can be directly integrated into territorial planning processes, infrastructure investment prioritization, cost–benefit analyses of risk reduction measures, and insurance or financial retention schemes. Given the comprehensive coverage of the building and critical infrastructure portfolio, and the internal consistency of the model, the generated indicators are suitable for relative comparisons across sectors, subsectors, and geographic areas, as well as for tracking aggregated risk over time.

2. Management, safeguarding, and traceability of exposure data

Given that the quality and level of disaggregation of the exposure data constitute one of the main assets of the study, it is recommended to establish formal procedures for its maintenance, updating, and version control. This includes defining institutional responsibilities, setting periodic update protocols (for example, in response to new construction, changes in use, or asset retirement), and implementing traceability mechanisms to document modifications made to the original inventory.

The consistency and continuity of the exposure database are necessary conditions to ensure that future risk updates remain comparable to current results and to establish a minimum quality standard for subsequent assessments.

3. Definition of institutional guidelines for risk interpretation and communication

It is recommended that local institutions establish clear and consistent guidelines for the interpretation, use, and communication of probabilistic risk results derived from the study. These guidelines should

specify the scope and limitations of metrics such as AAL and PML, the appropriate levels of aggregation for institutional use, and the contexts in which results may inform technical, financial, or strategic decision-making. Consistent interpretation of risk helps prevent inappropriate or contradictory use of results across institutions and facilitates communication with non-technical decision-makers.

4. Periodic updating of hazard models and alignment with new technical information

It is recommended that the hazard models used in this study be reviewed and periodically updated, incorporating new hydrometeorological, geotechnical, seismological, or topographic information as it becomes available. Since the current models were developed at an appropriate resolution for the cantonal scale and under consistent technical criteria, updates can be implemented in a modular manner while preserving the overall structure of the risk model. This process will progressively improve the spatial and probabilistic representation of hazards and ensure that results remain relevant in light of evolving technical knowledge or environmental conditions.

5. Strengthening institutional capacities and ownership of the risk model

To ensure the sustainability of the results, it is recommended to invest in strengthening technical capacities within local institutions, focused on understanding, interpreting, and operationally using probabilistic metrics. This includes training in risk modeling concepts and result interpretation, as well as in the use of the geospatial inputs generated and made available in the project dataset.

6. Use of the canton of Heredia as a catalyst for replicating cantonal-scale risk assessments

It is recommended that the canton of Heredia be used as a pilot and catalytic experience for replicating multi-hazard risk assessments in other cantons of the country, even where data conditions may be less favorable in terms of quality, coverage, or level of disaggregation. The methodology applied, the structure of the risk model, and the lessons learned during the development of this study constitute valuable inputs for defining scalable and adaptable approaches across varying data contexts. The progressive replication of this type of exercise would help strengthen a homogeneous territorial risk perspective and guide future efforts in data collection and institutional strengthening in cantons facing greater limitations.

3 SITE EFFECTS MODEL FOR HEREDIA

As added value within this consultancy and considering the scale of the seismic risk model for the canton of Heredia, the development of an approximate site effects model was proposed. This model allows for simplified consideration of the modifying effect of shallow soil dynamic response on strong ground motion generated by earthquakes.

Site effects are highly relevant in earthquake engineering because soil response generally leads to amplification of effective accelerations at the foundation level of infrastructure. As a result, seismic demands on exposed elements increase compared to effective accelerations at the level of firm rock.

The methodology applied to develop the site effects model for Heredia is based on the methodological proposal for seismic microzonation studies by Bernal (2014) and Bernal & Cardona (2015), and can be summarized in the following steps:

1. *Definition of the soft soil deposit geometry:* Based on available geological and geophysical information from previous studies in nearby areas—mainly the seismic microzonation studies of San José—a simplified model of soft soil deposit thickness is established. This model defines the underlying topography of the deposit, that is, the contact with firm rock, from which a three-dimensional geometric model can be constructed to determine the total soil depth at each point within the city.
2. *Geotechnical information:* Given the simplified nature of the proposed model and the impossibility of conducting a field investigation campaign including boreholes at multiple locations, the best available geotechnical information from nearby areas is used to define a general geotechnical condition for the canton. Although spatial variability in soil properties within the canton is likely, this assumption is considered sufficient for approximating the effect of soil on strong ground motion.
3. *Selection of seismic signals:* To evaluate soil behavior within the nonlinear range, seismic signals with different levels of peak ground acceleration are defined. These signals do not necessarily need to be compatible with the bedrock-level hazard; instead, they are selected solely to induce nonlinear behavior in the soils.
4. *Definition of calculation sites:* At each calculation site, synthetic stratigraphic profiles are generated based on the geometry of geological formations and the geotechnical information available for the entire city.
5. *Evaluation of dynamic response:* For each synthetic stratigraphy at each calculation site, one-dimensional dynamic response is evaluated using a nonlinear behavior model for each selected seismic signal. At each node, Fourier spectrum transfer functions are obtained. These are calculated for different levels of peak acceleration at the base of the deposit, thereby capturing the nonlinear behavior of soils.
6. *Calculation of seismic hazard at each site:* Seismic hazard at each location is calculated through spectral transformation of the hazard at the firm rock level, incorporating the transfer function

corresponding to each site to obtain the surface response spectrum. At this stage, the general seismic hazard model selected in this consultancy is also used, namely the ASLAC model (Salgado et al., 2018).

The following sections detail the information, procedures, and assumptions considered in each of the steps described above.

3.1 Geometric–Geotechnical Model

The geometric and geotechnical model is an essential component in the modeling of site effects in cities or metropolitan areas. The extremely high spatial variability of geotechnical conditions—particularly in terms of soil thickness, stiffness, and nonlinear behavior—is widely recognized. Characterizing these variations typically requires substantial investment in geotechnical and geophysical field campaigns. Such investigations are common in seismic microzonation studies.

In this case, however, no site-specific field data of this nature are available, and their acquisition falls well beyond the scope of this consultancy. Given the need to incorporate site effects, and the reality of not having field data to geotechnically and geophysically characterize the territory, it becomes necessary to rely on assumptions and approximations based on timely available information.

In the year 2000, the Seismic Microzonation Study of the Metropolitan Area of San José was conducted. This research project aimed to obtain results regarding seismic hazard and soil dynamic behavior in the Metropolitan Area of San José, where the majority of Costa Rica’s population is concentrated and where the country’s main socioeconomic activities take place.

More recently, Arroyo-Solórzano (2023) and Benito et al. (2025) proposed a seismic zonation for the Greater Metropolitan Area of San José, based on the soil classification system defined by NERPH (2020). Figure 6 presents this general soil classification, showing that soils in the southeastern portion of the canton correspond to type D or DE soils, with typical thicknesses between 10 and 20 meters and shear-wave velocities between 200 and 300 m/s (according to NERPH, 2020).

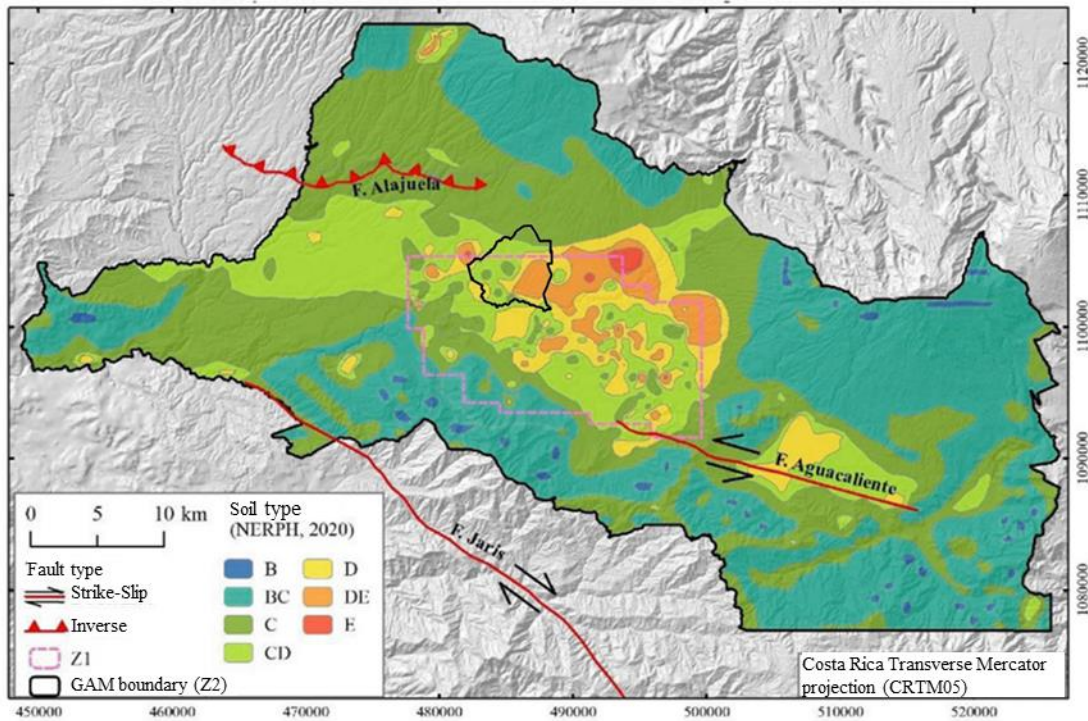


Figure 6. Seismic microzonation for the Greater Metropolitan Area of San José. Adapted from Arroyo-Solórzano (2023) to include the outline of the urban area of the canton of Heredia.

This zonation was modified to account for the topography of local landforms, which alters deposit thickness over short distances. For this purpose, an equivalent soil thickness was approximated as a function of topographic slope using the following empirical formula:

$$e = \frac{30}{s} \quad \text{Equation 8}$$

where e is the thickness in meters and s is the topographic slope in degrees. This equation is a proposal by the consultant, derived from prior experience in modeling site effects. In this way, the thickness associated with topographic slope is combined with the characteristic thickness derived from the geotechnical zonation, resulting in a proposed distribution of approximate soil thicknesses within the canton, as shown in Figure 7.

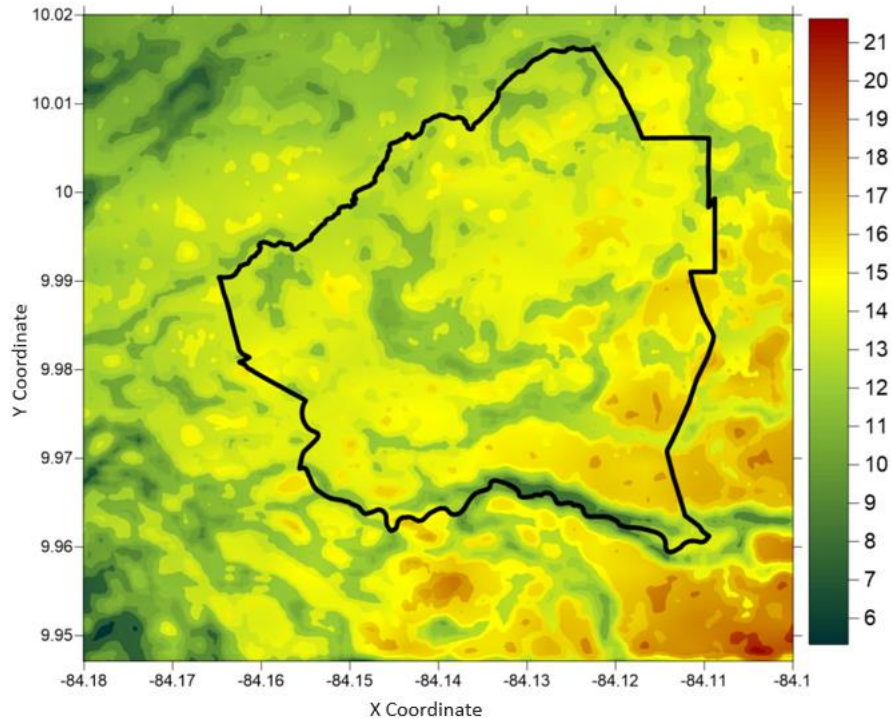


Figure 7. Proposed approximate soft-soil thicknesses in Heredia. Scale in meters.

As mentioned previously, it is necessary to geometrically model the soft deposit throughout the entire extent of the canton. The lower boundary corresponds to the elevation at which the materials considered within the soft soil thickness are presumed to end; therefore, the previously defined thickness model allows this elevation to be determined. The ground surface elevation constitutes the upper boundary of the computational domain. This makes it possible to determine the deposit depth at any location, resulting in a three-dimensional subsurface model.

Based on the NEHRP classification provided in Arroyo-Solórzano (2023) and Benito et al. (2025), linear depth-varying shear-wave velocity profiles are defined to match the corresponding V_{s30} value of each soil class. That is, the average velocity within the upper 30 meters (or until reaching bedrock) falls within the range of the respective class at each location.

Although this represents a coarse approximation, since shear-wave velocity does not necessarily vary linearly with depth, it is considered sufficient for the purposes of this assessment.

Based on the shear-wave velocity (V_s) classification and the thickness model (H), it is possible to determine the small-strain fundamental soil vibration period, T , as follows:

$$T = \frac{4H}{V_s} \quad \text{Equation 9}$$

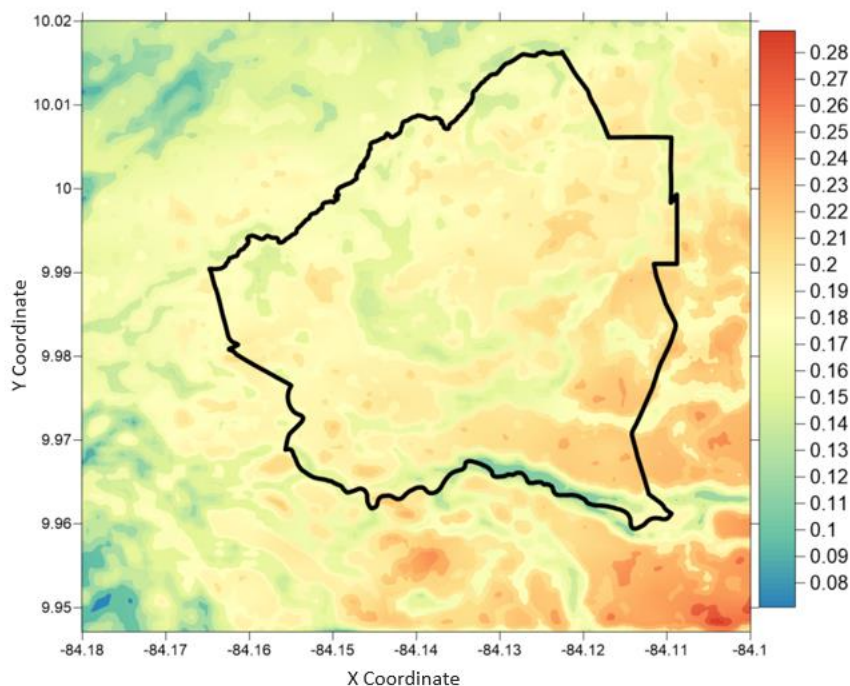


Figure 8. Fundamental soil vibration period in Heredia. Scale in seconds.

3.2 Synthetic Stratigraphies

The applied site effects evaluation methodology is based on the generation of synthetic stratigraphies at arbitrary locations, sites that have not been previously explored. These stratigraphies constitute the foundation for evaluating the dynamic response of soft soils.

Synthetic stratigraphies are constructed based on the geometric–geotechnical model. At any location within the canton (i.e., at any calculation point), a synthetic stratigraphic profile can be generated. This profile consists of a sequence of geotechnical property values corresponding to the specific depth under consideration.

The geotechnical properties included in this model are limited to two parameters: unit weight and shear-wave velocity. With these properties, each soil layer is fully defined for dynamic response modeling. Since the stratigraphy is composed of multiple layers, it is characterized through depth profiles of shear-wave velocity and unit weight.

Finally, stiffness degradation and damping models are assigned to approximate nonlinear soil behavior under large shear strains. The model proposed by Flores (2025) is employed, which, although specifically developed for the soils of Heredia, is applicable to volcanic soils in mountainous regions.

3.3 Input Ground Motions

Real accelerogram records are used to evaluate the dynamic response of the simulated stratigraphies at each calculation location. These signals are not intended to be representative of the seismic hazard in Heredia; rather, they are selected to cover a broad range of amplitudes and frequency contents, allowing nonlinear response of the soft soil deposit to be induced under seismic loading. In other words, these signals do not have—and are not required to have—any direct relationship with the bedrock-level hazard.

Earthquakes from different regions worldwide were selected, including both crustal and subduction sources. The records were scaled to peak ground accelerations of 0.05g, 0.1g, 0.2g, or 0.4g, depending on the original maximum acceleration of each signal. This approach standardizes the intensity level applied at the base of the simulations without drastically altering the intrinsic characteristics of the selected records.

Table 3 and Table 4 present the main characteristics of the seismic records used, including: record identification, event date, Magnitude, hypocentral distance, duration, original peak acceleration, and scaled peak acceleration (i.e., the level to which each record was adjusted). Figure 9 through Figure 12 display the selected ground motion records.

Table 3. Selected signals from crustal sources

Name	ID Record	Country	Date	Magnitude	Distance	Duration	Amax	Amax Used
					(km)	(seg)	(g)	(g)
A01	Chalfant Valley	U.S.A	21/07/1986	6.2	50	39.81	0.051	0.05
A02	Georgia	U.S.S.R	15/06/1991	6.2	52	38.17	0.046	0.05
A03	Palm Springs	U.S.A	08/07/1986	6	63	24	0.053	0.05
A04	Anza	U.S.A	08/07/1986	6	26	24	0.113	0.1
A05	Armenia Bocatoma	Colombia	19/01/1999	6.2	42	31.92	0.084	0.1
A06	Imperial Valley	U.S.A.	15/10/1979	6.5	36	28.28	0.109	0.1
A07	Irpinia	Italia	23/11/1980	6.5	33	36.34	0.199	0.2
A08	Whittier Narrows	U.S.A	10/01/1987	6	10	29.96	0.199	0.2
A09	San Fernando	U.S.A	09/02/1971	6.6	27	29.66	0.212	0.2
A10	Coalinga	U.S.A.	22/07/1983	5.7	12	21.3	0.375	0.4
A11	Northridge	U.S.A.	17/01/1994	6.7	35	30.33	0.493	0.4
A12	Park Field	U.S.A.	28/06/1966	6.1	10	30.33	0.356	0.4

Table 4. Selected signals from subduction sources

Name	ID Record	Country	Date	Magnitude	Distance	Duration	Amax	Amax Used
					(km)	(seg)	(g)	(g)
S01	Nuxco	México	15/07/1996	6.5		83	0.049	0.05
S02	Ocotito	México	14/09/1995	7.2		61	0.059	0.05
S03	Zihuatán antejo	México	10/12/1994	6.6		34.05	0.053	0.05
S04	Paraíso	México	25/09/1984	6.5		36.67	0.102	0.1
S05	Red Smart	Taiwán	12/06/1985	6.5	45	27.15	0.142	0.1
S06	La Unión	México	10/12/1994	6.6		54.98	0.092	0.1
S07	Caleta	México	09/08/2000	6.7		42.21	0.194	0.2
S08	Ocotito	México	25/04/1989	6.5		53.16	0.195	0.2
S09	Copala	México	24/10/1993	6.2		58.94	0.292	0.4
S10	Las Vigas	México	25/04/1989	6.5		34.43	0.345	0.4

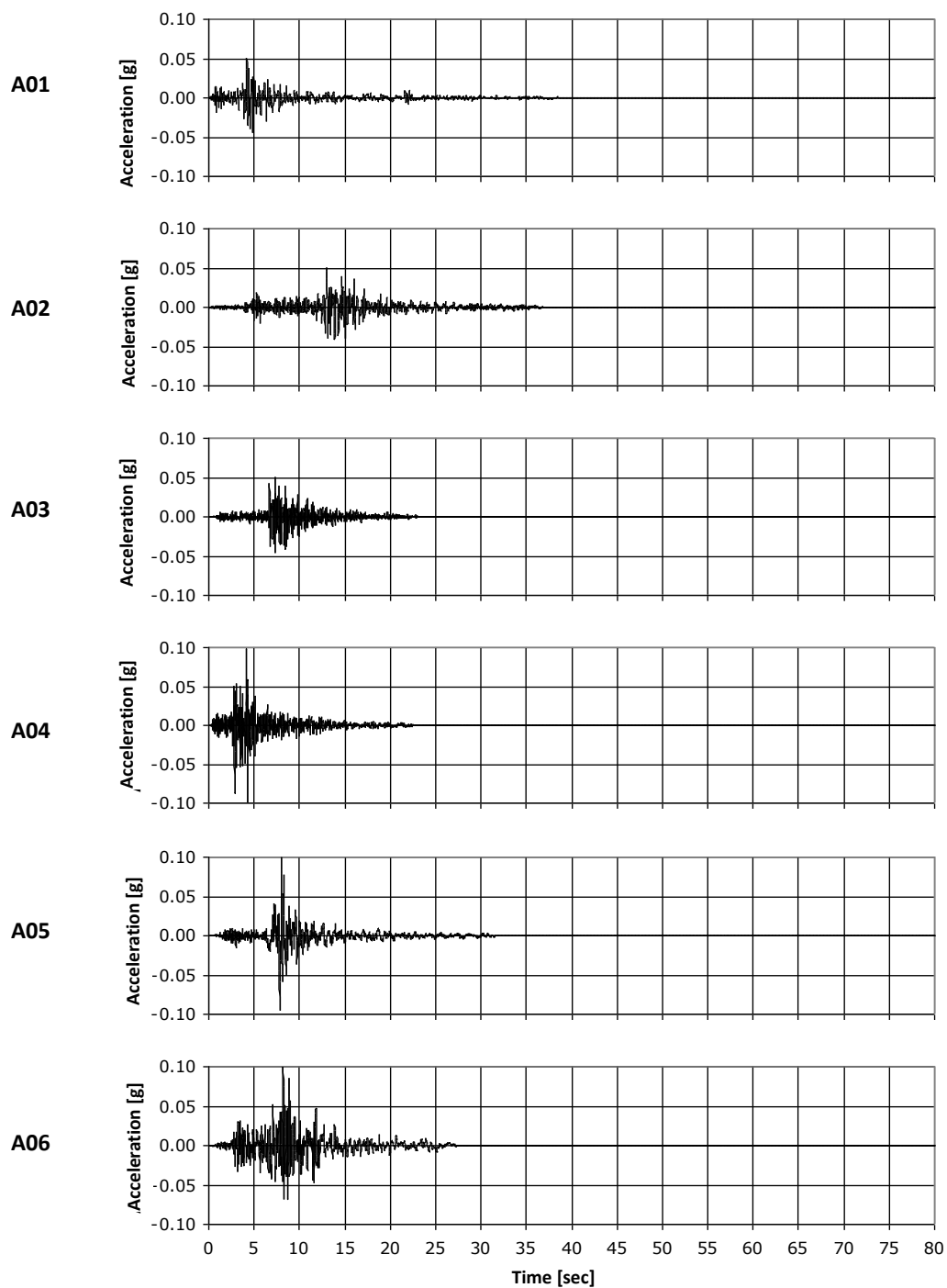


Figure 9. Crustal source signals

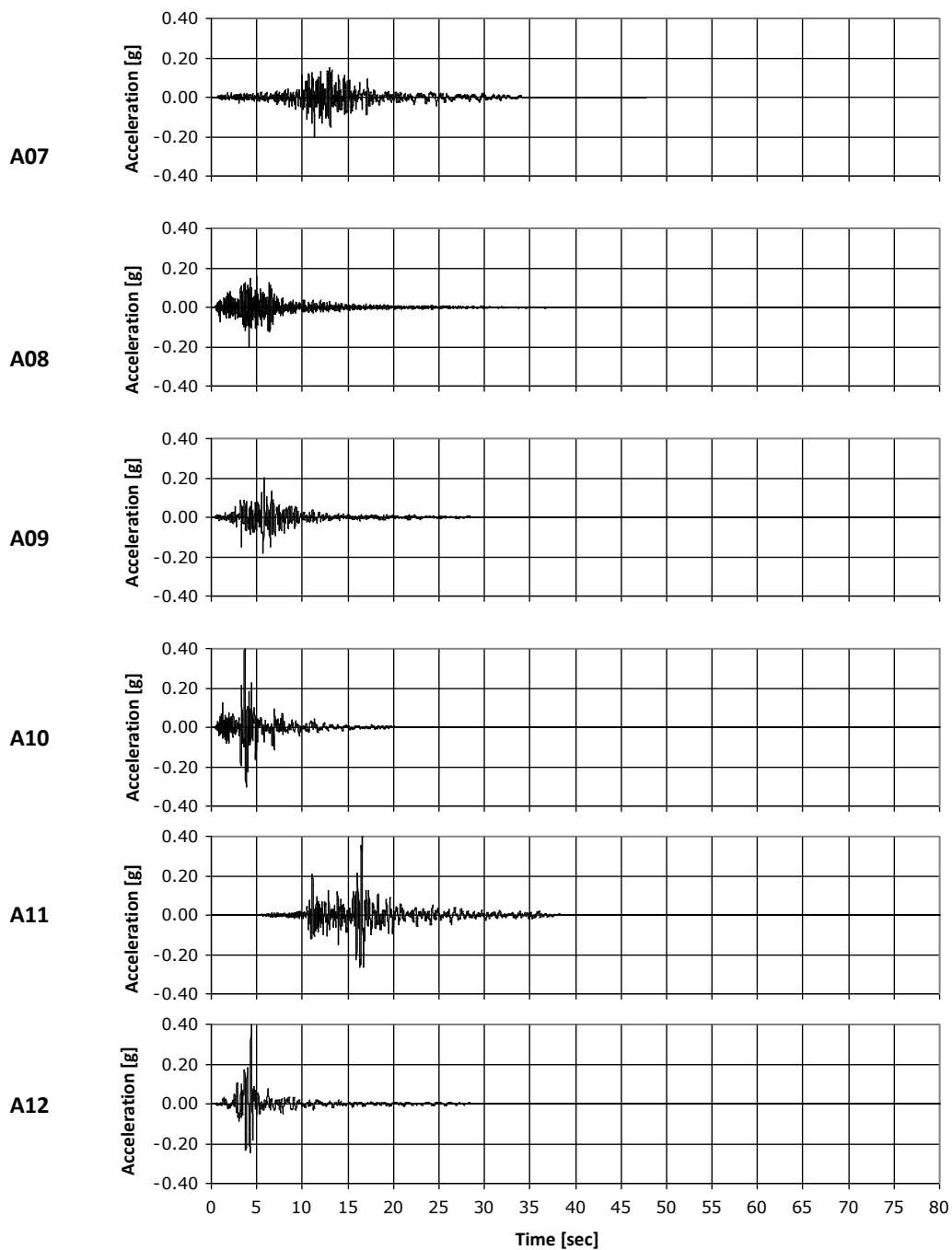


Figure 10. Crustal source signals.

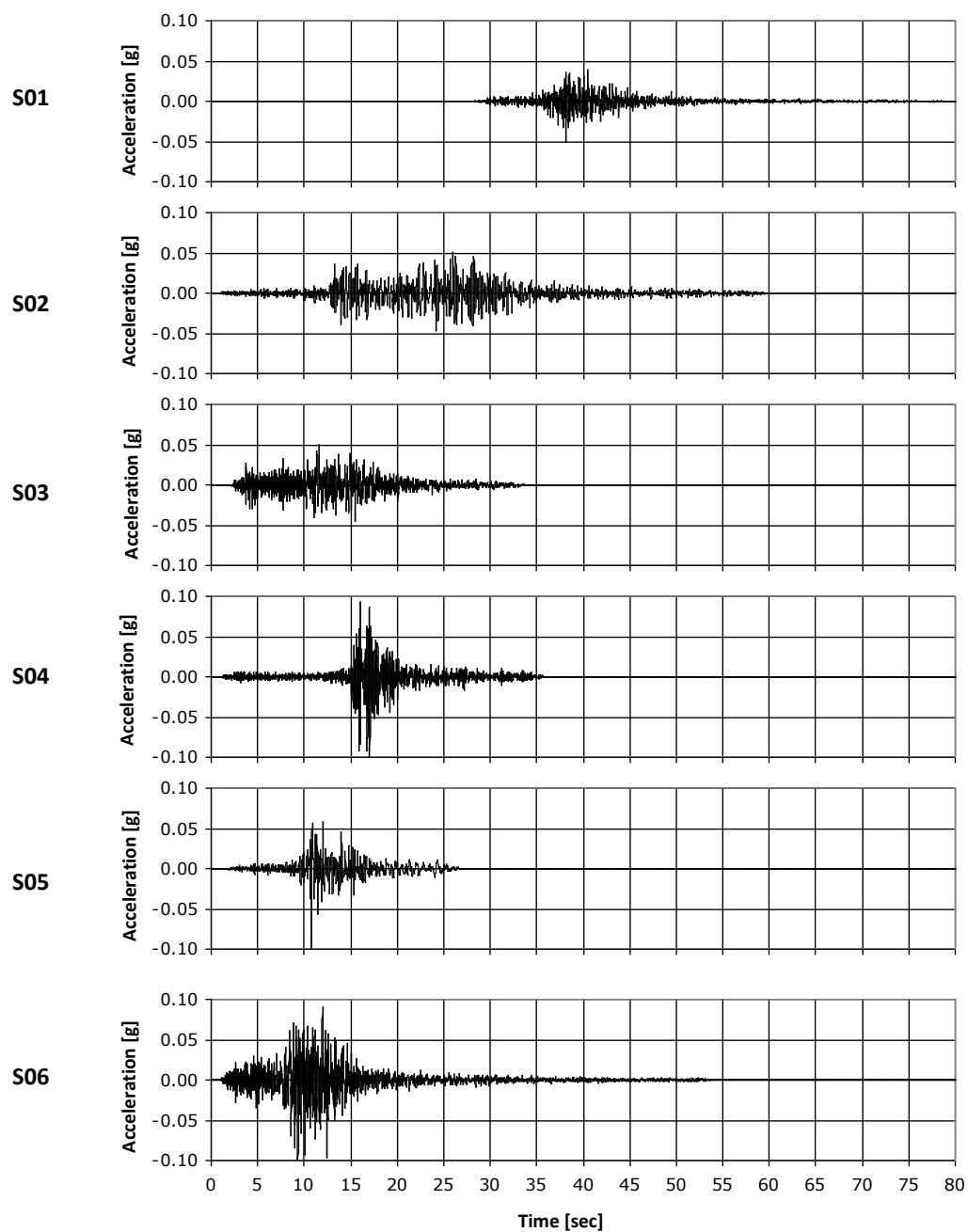


Figure 11. Subduction source signals.

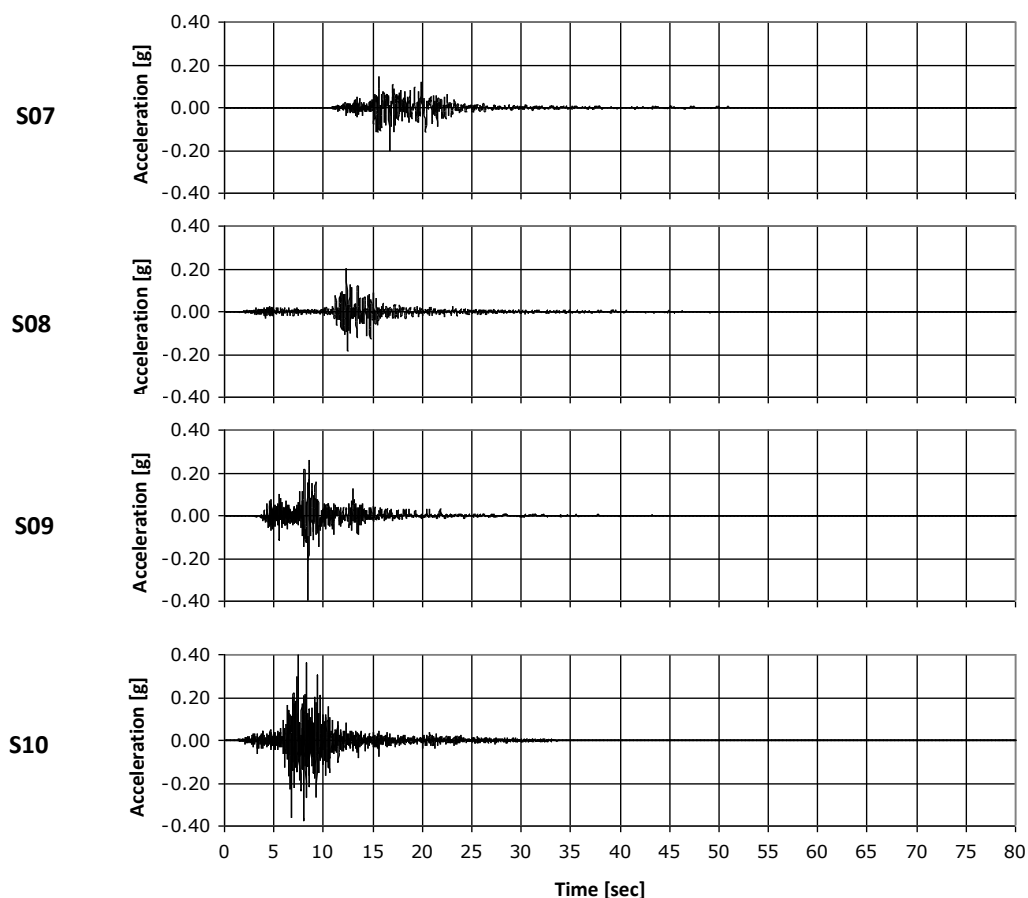


Figure 12. Subduction source signals.

3.4 Dynamic Response Calculation

For each stratigraphy, one-dimensional dynamic response is computed using the equivalent linear analysis method. This method, originally proposed by Harry Seed and Izzat Idriss (Idriss & Seed, 1968; Seed & Idriss, 1970), remains one of the most widely used approaches for evaluating soil response in the nonlinear range.

In this method, the linear response of the soil profile is first calculated. Through an iterative process, soil properties—specifically shear stiffness and damping—are adjusted according to constitutive nonlinear behavior models (stiffness degradation and damping curves), as illustrated in Figure 13.

In this study, the elastic response is calculated using the Thompson–Haskell propagator matrix method (Thompson, 1950; Haskell, 1953), which allows computation of linear Fourier spectrum transfer functions for a layered medium. This method provides a computationally efficient solution in the frequency domain.

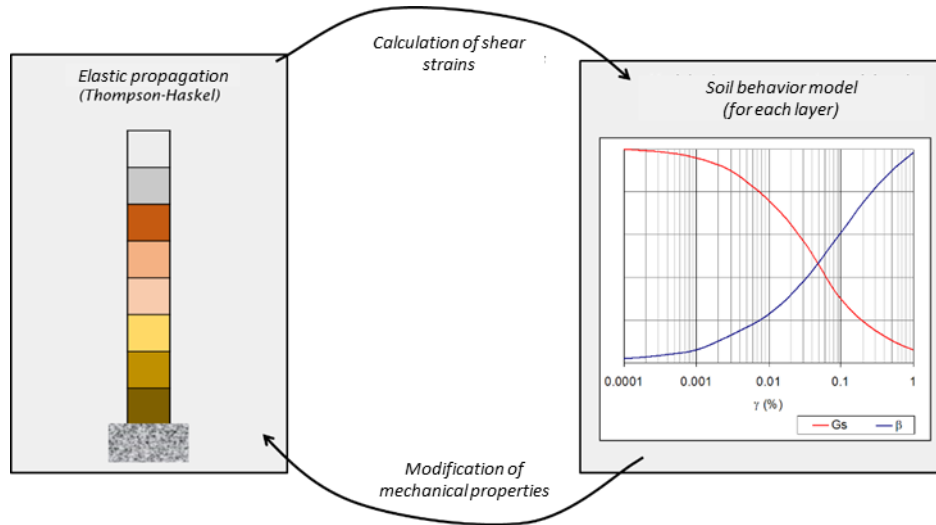


Figure 13. Illustration of the iterative process for evaluating one-dimensional dynamic response in the nonlinear range.

At each calculation location, dynamic response was evaluated, resulting in a site-by-site dataset consisting of:

- Strain-compatible properties (shear modulus and damping) for each accelerogram considered
- Surface acceleration response spectra
- Fourier spectrum transfer functions
- Surface accelerograms

Figure 14 through Figure 17 present the information obtained for a calculation site in Heredia, as displayed in the modeling software *Seismic Microzonation Studio* (Bernal, 2014), developed by INGENIAR and integrated within the CAPRA ROBOT platform.

Resultados

Resultados por capa

Espectro de respuesta

Funciones de transferencia

Acelerogramas en superficie

Resultados por señal

Capas

Nombre	Dt (seg)	Df (Hz)	NTF
A01	0.020	0.012	4096
A02	0.020	0.012	4096
A03	0.020	0.012	4096
A04	0.020	0.012	4096
A05	0.020	0.012	4096
A06	0.020	0.012	4096

Propiedades del sitio

Roca

Gamma (ton/m3)2.2

Vs (m/s)1000

Sitio

Ubicación-84.139294896849, 9.95570752

Nivel freático(m)32.025173187713

Sito

Tipo de valorPromedio

¿Sitio en roca?No

Tipo de valor

Tipo de valor usado en la asignación de propiedades geotécnicas

Id de capa	Tipo de suelo	Profundidad (m)	Gamma (ton/m3)	Vs inicial (m/s)	Vs final (m/s)
1	Suelo 1	0.5	1.19	106.00	88.72
2	Suelo 1	1.5	1.21	130.00	104.88
3	Suelo 1	2.5	1.24	154.00	125.05
4	Suelo 1	3.5	1.25	166.00	133.79
5	Suelo 1	4.5	1.27	190.00	158.02
6	Suelo 1	5.5	1.30	214.00	182.17
7	Suelo 1	6.5	1.31	226.00	193.03
8	Suelo 1	7.5	1.34	250.00	216.53
9	Suelo 1	8.5	1.36	274.00	241.38
10	Suelo 1	9.5	1.38	286.00	254.00
11	Suelo 1	10.5	1.40	310.00	279.82
12	Suelo 1	11.5	1.43	334.00	304.46
13	Suelo 1	12.5	1.44	346.00	316.04
14	Suelo 1	13.5	1.46	370.00	340.85
15	Suelo 1	14.5	1.49	394.00	365.61
16	Suelo 1	15.5	1.50	406.00	377.62

Figure 14. Strain-compatible geotechnical properties. Seismic microzonation studio

Resultados

Resultados por capa | **Espectro de respuesta** | Funciones de transferencia | Acelerogramas en superficie

Desplazamiento

Velocidad

Aceleración

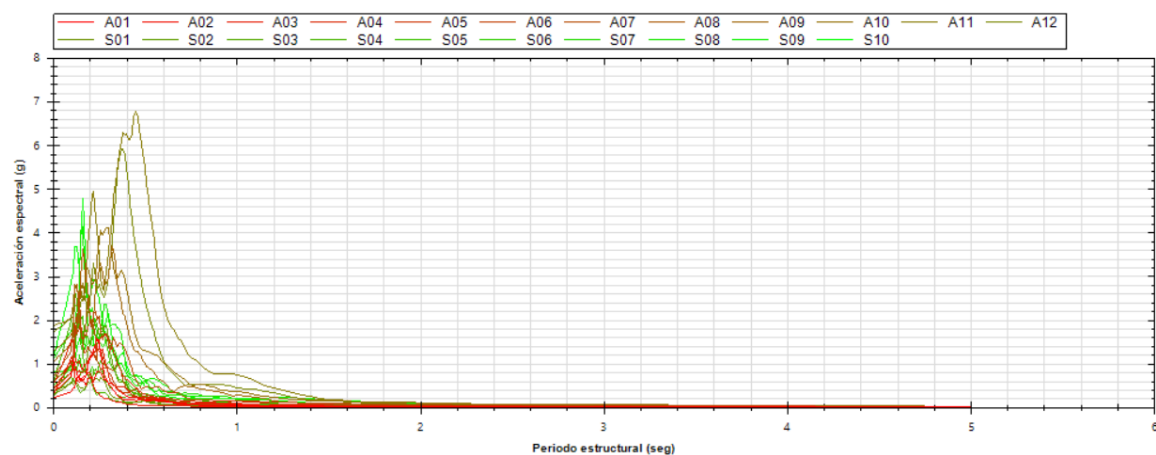


Figure 15. Surface acceleration spectra. Seismic microzonation studio

Resultados

Resultados

Resultados por capa | **Espectro de respuesta** | **Funciones de transferencia** | Acelerogramas en superficie

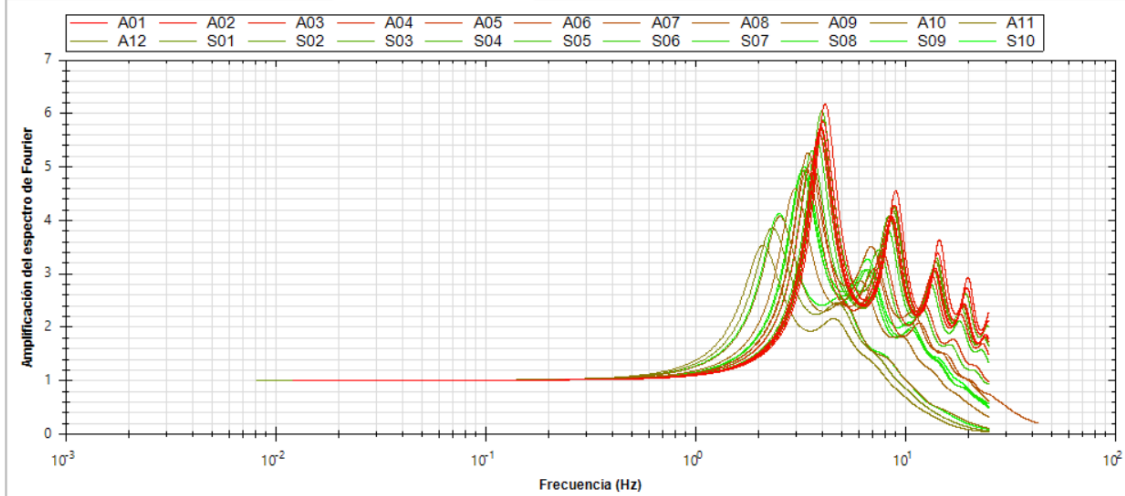


Figure 16. Fourier Spectrum Transfer Functions. Seismic microzonation studio

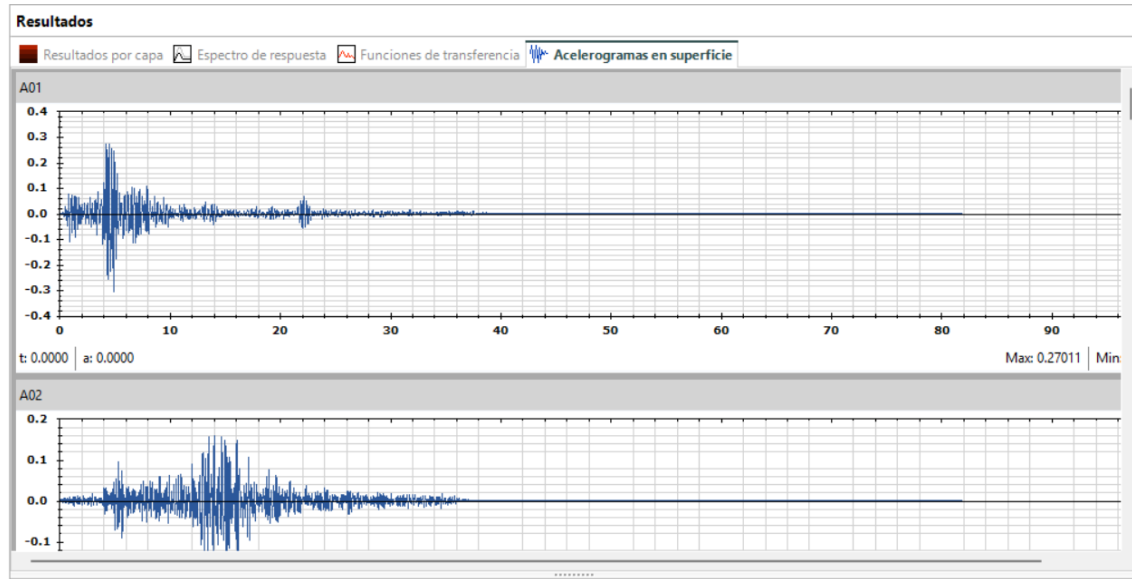


Figure 17. Surface accelerograms. seismic microzonation studio

3.5 Seismic Hazard Calculation

For hazard assessment, the classical integration procedure is used. This approach considers the different possible earthquake locations included in the model, where the hypocenter is defined at the centroid of the sub-sources generated within the main seismic sources. By applying these concepts, it is possible to determine the exceedance rates of any intensity measure and to obtain standard representations of seismic hazard, such as hazard maps or uniform hazard spectra. In this study, seismic hazard was evaluated using the R-CRISIS program (Ordaz et al., 2017), which is part of the CAPRA ROBOT platform.

Figure 18 through Figure 20 present surface-level uniform hazard maps in terms of peak ground acceleration (PGA) for return periods of 100, 500, and 1,000 years. These maps illustrate the spatial variation of seismic intensities within the canton of Heredia, which is primarily controlled by the dynamic response of the soils.

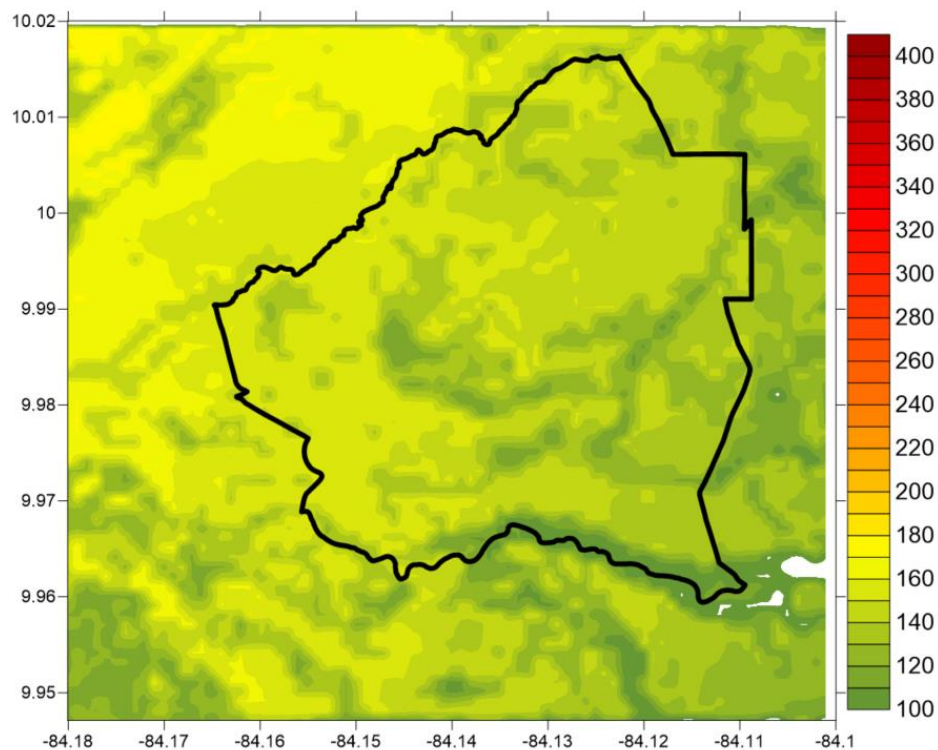


Figure 18. Uniform hazard map with a 100-Year Return Period. PGA in cm/s^2 .

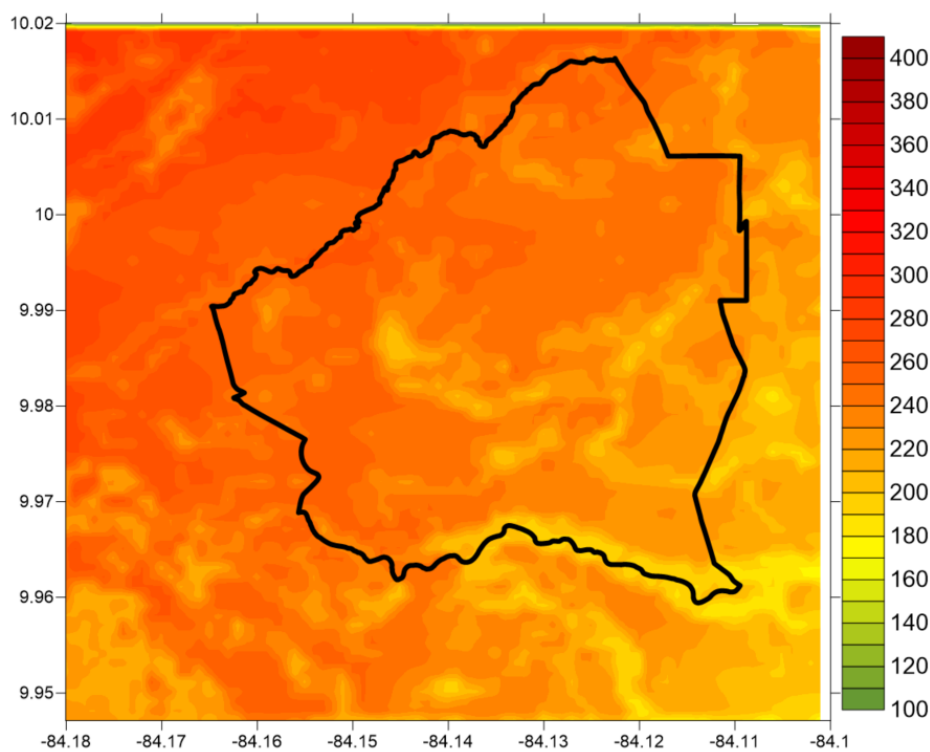


Figure 19. Uniform hazard map with a 500-Year Return Period. PGA in cm/s^2 .

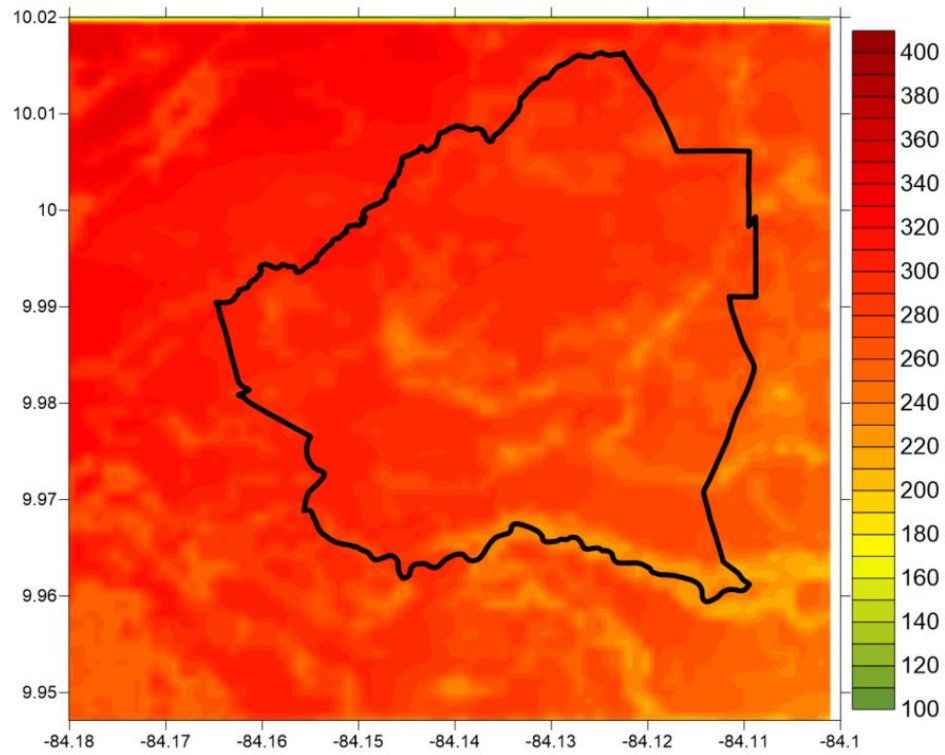


Figure 20. Uniform hazard map with a 1000-Year Return Period. PGA in cm/s^2 .

4 LANDSLIDE SUSCEPTIBILITY MODEL FOR HEREDIA

As added value within this consultancy, the inclusion of landslide hazard in the risk model for the canton of Heredia was agreed upon. This involves considering landslides triggered by both earthquakes and intense rainfall.

In general terms, slope stability assessment requires understanding four fundamental governing aspects: i) the loads acting on the blocks or portions of material that may slide; ii) the role of water in modifying the mechanical properties of slope materials; iii) the geological structure of the site and anthropogenic modifications; and iv) external triggering events, particularly earthquakes and excessive rainfall.

The first three aspects mentioned can be condensed into the concept of susceptibility, which reflects the intrinsic conditions that favor instability. The trigger, in contrast, is an external factor acting on the slope and is addressed through probabilistic models of seismic hazard and rainfall occurrence. Landslide hazard is therefore determined as a probability of failure that depends on both susceptibility and the exceedance probability of the trigger, that is, the probability that, given the occurrence of a triggering event, a certain intensity threshold is exceeded. In other words, a landslide hazard model requires the definition of three components: susceptibility, trigger model, and threshold model.

The triggers (earthquake and rainfall) already have probabilistic models within this consultancy. In the seismic case, the ASLAC model (Salgado et al., 2018) is used, as previously mentioned. Rainfall is modeled through daily-scale simulations based on historical climate data, which are modified according to climate change scenarios depending on the climate condition considered (see Product 4 “Climate Hazard Models”).

However, the development of new models for susceptibility and threshold components falls outside the scope of this consultancy. Therefore, it was necessary to select pre-existing models for these components.

As presented in Product 2 “Review geohazard data and proposal on applying in risk assessment”, the selected model is the one developed by Nadim et al. (2023) and implemented globally by INGENIAR within the framework of the Global Infrastructure Resilience Index (GIRI) project of the Coalition for Disaster Resilient Infrastructure (CDRI). This landslide hazard model is methodologically consistent with the requirements for risk modeling. It accounts for landslide susceptibility and provides appropriate triggering thresholds for probabilistic hazard assessment.

The GIRI-CDRI model therefore satisfies the minimum requirements for conducting a probabilistic hazard analysis. However, due to its relatively coarse spatial resolution, a downscaling process is necessary to enable its application within the context of the risk assessment for the canton of Heredia.

4.1 GIRI-CDRI Susceptibility Model

The GIRI-CDRI landslide susceptibility model covers the entire territory of Costa Rica through a mosaic of four rectangular grids of 5×5 degrees, with a spatial resolution of 90 meters. Within these grids, slope susceptibility is classified into five categories using the Mora–Vahrson (1994) method. At each pixel, landslide susceptibility is estimated as the annual probability of occurrence of a potentially destructive

landslide event. The susceptibility factors considered include topographic slope, lithology, vegetation cover, and soil moisture.

Susceptibility can be interpreted as the intrinsic probability of slopes to fail. This result reflects only susceptibility and therefore does not represent the actual probability of landslide occurrence, since triggering events have not yet been incorporated.

The susceptibility map obtained from GIRI-CDRI for Costa Rica is shown in Figure 21.

Five susceptibility categories are used, ranging from 1 = very low landslide susceptibility to 5 = very high susceptibility. These classes correspond to a classification based on landslide occurrence probabilities, whose definition requires the inclusion of triggering intensity ranges, as described below.

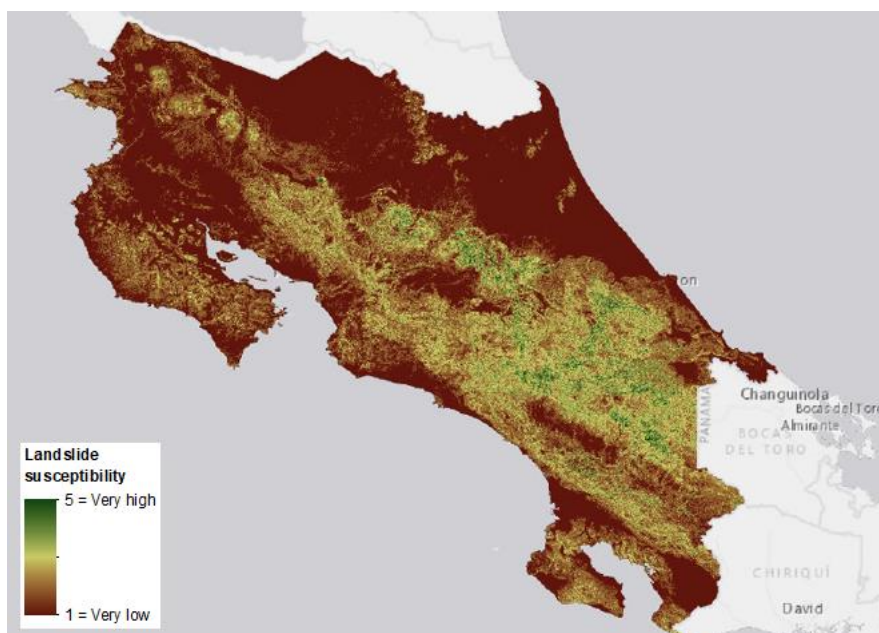


Figure 21. Landslide susceptibility map of Costa Rica from the CDRI–GIRI Project Led by INGENIAR

4.2 GIRI-CDRI Triggering Threshold Model

The triggering threshold model considered in GIRI-CDRI, as described in Palau et al. (2022), is a simplified approach that correlates susceptibility categories with intensity levels of triggering phenomena in order to establish the corresponding probability of landslide occurrence.

In this sense, it represents an extension of the susceptibility model, where a probability of landslide occurrence is assigned for different levels of triggering hazard intensity.

Table 5 presents the landslide probabilities according to GIRI-CDRI, expressed as a function of standardized 24-hour precipitation.

Table 5. Rainfall–Landslide threshold considered

Range P_n	Susceptibility category				
	Susc. 1	Susc. 2	Susc. 3	Susc. 4	Susc. 5
$P_n < 0.3$	0%	0%	0%	0%	0%
$0.3 \leq P_n < 2.0$	0%	1%	2%	3%	5%
$2.0 \leq P_n < 3.7$	0%	2%	3%	5%	10%
$3.7 \leq P_n < 5.0$	0%	3%	5%	10%	15%
$P_n > 5.0$	0%	5%	10%	15%	20%

In the case of the seismic trigger, a similar classification is used but based on peak ground acceleration (PGA). PGA is correlated with the susceptibility categories to define the probability of occurrence of earthquake-triggered landslides.

This threshold relationship is presented in Table 6. PGA is expressed as a fraction of gravitational acceleration (g).

Table 6. Acceleration–Landslide threshold considered

Range PGA	Susceptibility category				
	Susc. 1	Susc. 2	Susc. 3	Susc. 4	Susc. 5
$0.05g \leq PGA < 0.15g$	0%	0%	0%	0.1%	0.5%
$0.15g \leq PGA < 0.25g$	0%	0%	0.1%	0.5%	1%
$0.25g \leq PGA < 0.35g$	0%	0.1%	0.5%	1%	5%
$0.35g \leq PGA < 0.45g$	0%	0.5%	1%	5%	10%
$PGA \geq 0.45g$	0%	1%	5%	10%	40%

4.3 Downscaling for the Case of Heredia

A susceptibility model with a spatial resolution of 90 meters may be too coarse in the context of a detailed assessment, such as the risk model developed for the canton of Heredia. Ideally, a new susceptibility model should be generated at an appropriate scale, allowing incorporation of local terrain features and land-use conditions that may not be captured by the global model and that influence slope susceptibility. However, the development of such a model is not within the scope of this consultancy.

Therefore, a simplified downscaling process was applied by resampling susceptibility as a function of topographic slope.

The topographic data used were obtained from EOS Data Analytics. The dataset consists of a digital elevation model (DEM) with a spatial resolution of 4.7 meters and a maximum elevation within the canton of 1,166 meters above sea level. The digital elevation model was consulted for the entire canton of Heredia, for visualization purposes Figure 22 presents the DEM for the urban area of the Canton of Heredia.

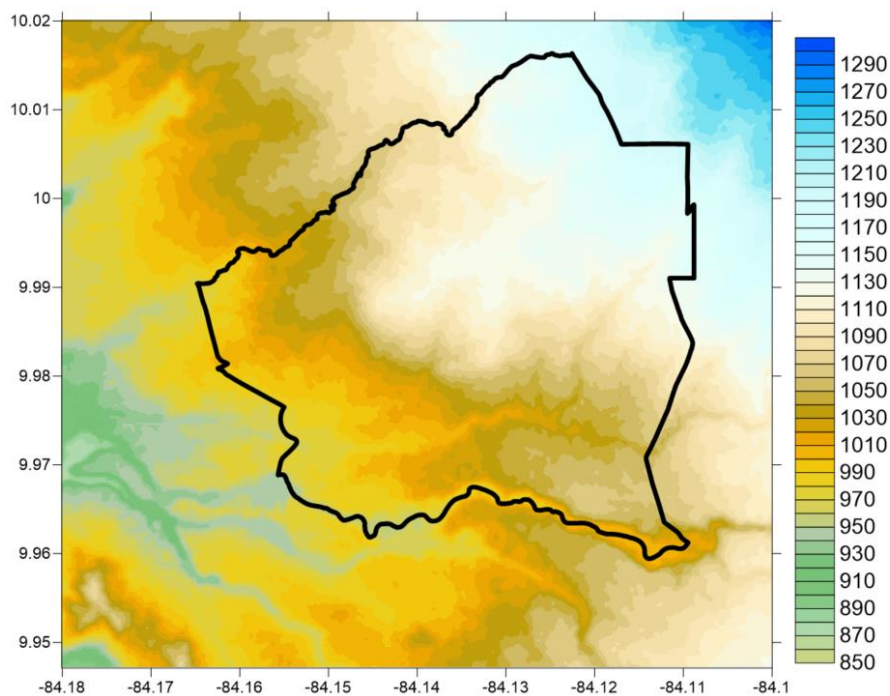


Figure 22. Digital Elevation Model with a spatial resolution of 4.7 meters for Heredia

From this DEM, topographic slopes were derived and used to reassign susceptibility values within the five categories defined in the GIRI-CDRI model.

The reassignment procedure was defined by the consulting team, in an arbitrary manner, based on professional judgment and experience, as follows:

$$Susc = \begin{cases} 1 & si \ s \leq 7^\circ \\ 2 & si \ 7^\circ < s \leq 20^\circ \\ 3 & si \ 20^\circ < s \leq 30^\circ \end{cases} \quad \text{Equation 10}$$

By applying this reassignment, the susceptibility model shown in

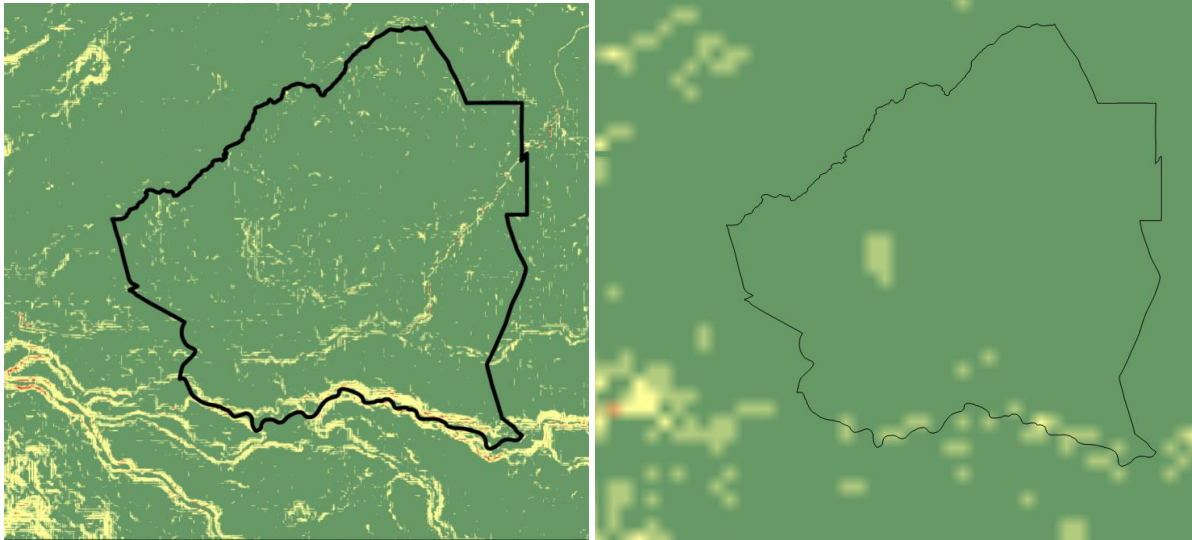
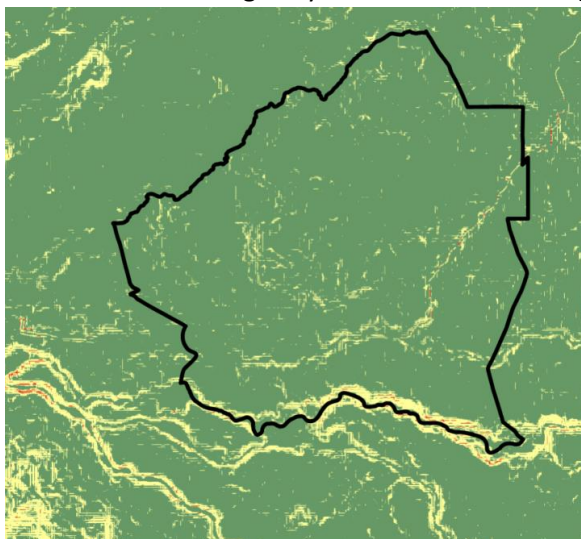


Figure 23 is obtained. The threshold model was maintained as originally defined in GIRI-CDRI (Palau et



al., 2022). For comparative purposes,

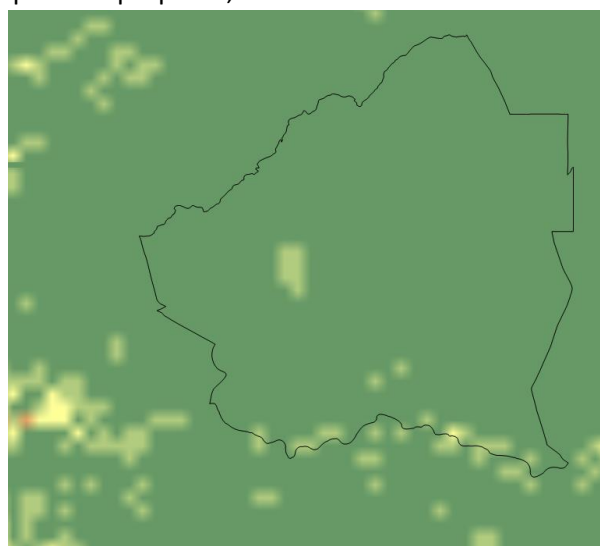


Figure 23 also shows the original susceptibility in the GIRI-CDRI model at the resolution of that dataset. As can be observed, the reclassification is consistent with the susceptibility levels (that is, no susceptibility levels higher than 3 are reported in the GIRI-CDRI model), but with a resolution more suitable for smaller-scale risk modeling.

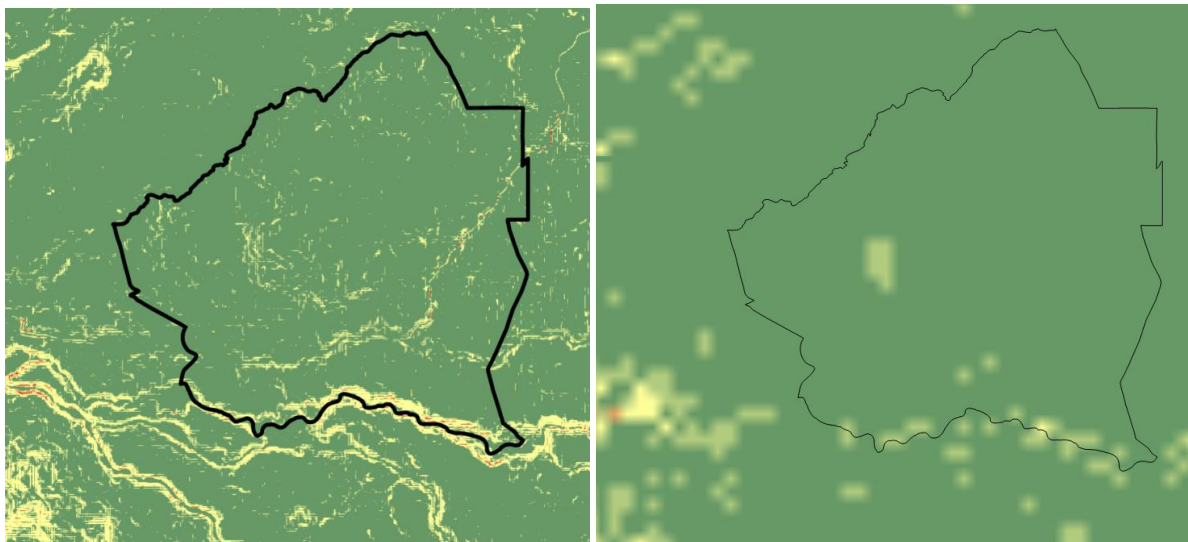


Figure 23. Left: Reduced-scale landslide susceptibility in the Canton of Heredia. Right: Susceptibility according to the GIRI-CDRI model. Green = 1. Yellow = 2. Red = 3.

5 RESULTS OF THE RISK ASSESSMENT

This section presents the results of the risk assessment for the portfolio of buildings and critical infrastructure in the canton of Heredia, in terms of Average Annual Loss (AAL) and Probable Maximum Loss (PML), considering earthquakes, riverine flooding (river overflow), pluvial flooding (surface water accumulation), and landslides triggered by earthquakes and intense rainfall.

For seismic hazard, as well as earthquake-triggered landslides, results are presented as losses not associated with any specific climate condition. However, for flooding (both riverine and pluvial) and rainfall-triggered landslides, it is necessary to incorporate the effects of climate change, which modifies the causal meteorological forcing and, therefore, alters the risk metrics.

Details regarding climate modeling and the incorporation of climate change into these hazards can be found in Product 4 “Climate Hazard Models” of this consultancy. Three global circulation models (GCMs), four greenhouse gas emission pathways, and three future target years were considered, resulting in a total of 36 possible future climate versions.

The models, emission pathways, and projection years are summarized in Table 7, including the abbreviated names used throughout this document to refer to the results associated with each climate scenario.

Table 7. Future climate scenarios considered for fluvial flood, pluvial flood, and rainfall-triggered landslides, and their abbreviations

GCM	Pathway	Target year	Abbreviation	GCM	Pathway	Target year	Abbreviation
EC-Earth3	SSP1-2.6	2035	EC-SSP1-35	GFDL-ESM4	SSP3-7.0	2050	GFDL-SSP3-50
EC-Earth3	SSP2-4.5	2035	EC-SSP2-35	GFDL-ESM4	SSP5-8.5	2050	GFDL-SSP5-50
EC-Earth3	SSP3-7.0	2035	EC-SSP3-35	GFDL-ESM4	SSP1-2.6	2100	GFDL-SSP1-100
EC-Earth3	SSP5-8.5	2035	EC-SSP5-35	GFDL-ESM4	SSP2-4.5	2100	GFDL-SSP2-100
EC-Earth3	SSP1-2.6	2050	EC-SSP1-50	GFDL-ESM4	SSP3-7.0	2100	GFDL-SSP3-100
EC-Earth3	SSP2-4.5	2050	EC-SSP2-50	GFDL-ESM4	SSP5-8.5	2100	GFDL-SSP5-100
EC-Earth3	SSP3-7.0	2050	EC-SSP3-50	MPI-ESM1-2-LR	SSP1-2.6	2035	MPI-SSP1-35
EC-Earth3	SSP5-8.5	2050	EC-SSP5-50	MPI-ESM1-2-LR	SSP2-4.5	2035	MPI-SSP2-35
EC-Earth3	SSP1-2.6	2100	EC-SSP1-100	MPI-ESM1-2-LR	SSP3-7.0	2035	MPI-SSP3-35
EC-Earth3	SSP2-4.5	2100	EC-SSP2-100	MPI-ESM1-2-LR	SSP5-8.5	2035	MPI-SSP5-35
EC-Earth3	SSP3-7.0	2100	EC-SSP3-100	MPI-ESM1-2-LR	SSP1-2.6	2050	MPI-SSP1-50
EC-Earth3	SSP5-8.5	2100	EC-SSP5-100	MPI-ESM1-2-LR	SSP2-4.5	2050	MPI-SSP2-50
GFDL-ESM4	SSP1-2.6	2035	GFDL-SSP1-35	MPI-ESM1-2-LR	SSP3-7.0	2050	MPI-SSP3-50
GFDL-ESM4	SSP2-4.5	2035	GFDL-SSP2-35	MPI-ESM1-2-LR	SSP5-8.5	2050	MPI-SSP5-50
GFDL-ESM4	SSP3-7.0	2035	GFDL-SSP3-35	MPI-ESM1-2-LR	SSP1-2.6	2100	MPI-SSP1-100
GFDL-ESM4	SSP5-8.5	2035	GFDL-SSP5-35	MPI-ESM1-2-LR	SSP2-4.5	2100	MPI-SSP2-100
GFDL-ESM4	SSP1-2.6	2050	GFDL-SSP1-50	MPI-ESM1-2-LR	SSP3-7.0	2100	MPI-SSP3-100
GFDL-ESM4	SSP2-4.5	2050	GFDL-SSP2-50	MPI-ESM1-2-LR	SSP5-8.5	2100	MPI-SSP5-100

5.1 Building Portfolio

5.1.1 Average Annual Loss (AAL)

Table 8 presents the complete list of AAL values for the entire building portfolio in the canton of Heredia. AAL values are shown by hazard, both in absolute monetary terms (Costa Rican colones) and in relative terms with respect to the total exposed value of the portfolio, expressed per thousand (‰).

For reference, the total exposed value of the building portfolio is ₡ 2.2 trillion (approximately USD 4,426 million²).

As mentioned previously, AAL represents the mean annual loss, that is, the annual compensation value that would be required to equal cumulative losses over the long term.

For example, in the case of riverine flooding under the baseline climate, the absolute AAL amounts to ₡ 1,613 million. This means that, if it were possible to distribute all long-term flood losses in the building portfolio of the canton of Heredia into a uniform annual payment under current climate conditions, that annual payment would correspond to this amount.

This annual loss, compared to the total exposed value of the portfolio, corresponds to 0.739‰. In practical terms, this means that for every ₡ 1,000 of value in the building portfolio, an average of ₡ 0.739 (approximately ₡ 1) is lost each year.

This relative indicator allows the Magnitude of the loss to be contextualized within the actual size of the portfolio. For reference, an AAL of 1‰ is typically considered near the threshold of what the insurance market regards as “insurable.” The results obtained fall within what is reasonable and expected for this type of hazard and building portfolio.

Table 8. Average Annual Loss by hazard and climate scenario. Values in millions of Costa Rican colones (CRC).

Hazard	Climate	AAL	AAL (‰)	Hazard	Climate	AAL	AAL (‰)
Earthquake		4,459	2.043	Pluvial flood	GFDL-SSP3-50	330	0.151
Fluvial flood	Climate base	1,613	0.739	Pluvial flood	GFDL-SSP5-50	336	0.154
Fluvial flood	EC-SSP1-35	1,569	0.719	Pluvial flood	MPI-SSP1-50	397	0.182
Fluvial flood	EC-SSP2-35	1,527	0.700	Pluvial flood	MPI-SSP2-50	464	0.213
Fluvial flood	EC-SSP3-35	1,511	0.692	Pluvial flood	MPI-SSP3-50	448	0.205
Fluvial flood	EC-SSP5-35	1,531	0.702	Pluvial flood	MPI-SSP5-50	375	0.172
Fluvial flood	GFDL-SSP1-35	1,636	0.750	Pluvial flood	EC-SSP1-100	345	0.158
Fluvial flood	GFDL-SSP2-35	1,580	0.724	Pluvial flood	EC-SSP2-100	330	0.151
Fluvial flood	GFDL-SSP3-35	1,557	0.714	Pluvial flood	EC-SSP3-100	322	0.148
Fluvial flood	GFDL-SSP5-35	1,567	0.718	Pluvial flood	EC-SSP5-100	317	0.145
Fluvial flood	MPI-SSP1-35	1,771	0.812	Pluvial flood	GFDL-SSP1-100	356	0.163
Fluvial flood	MPI-SSP2-35	1,893	0.868	Pluvial flood	GFDL-SSP2-100	343	0.157
Fluvial flood	MPI-SSP3-35	1,822	0.835	Pluvial flood	GFDL-SSP3-100	303	0.139
Fluvial flood	MPI-SSP5-35	1,751	0.803	Pluvial flood	GFDL-SSP5-100	296	0.136
Fluvial flood	EC-SSP1-50	1,553	0.711	Pluvial flood	MPI-SSP1-100	432	0.198
Fluvial flood	EC-SSP2-50	1,546	0.709	Pluvial flood	MPI-SSP2-100	394	0.181
Fluvial flood	EC-SSP3-50	1,491	0.683	Pluvial flood	MPI-SSP3-100	392	0.180

² Value calculated using an average exchange rate for the month of December 2025 corresponding to 490 colones per dollar.

Hazard	Climate	AAL	AAL (‰)	Hazard	Climate	AAL	AAL (‰)
Fluvial flood	EC-SSP5-50	1,495	0.685	Pluvial flood	MPI-SSP5-100	432	0.198
Fluvial flood	GFDL-SSP1-50	1,598	0.732	Earthquake-triggered landslide		59	0.027
Fluvial flood	GFDL-SSP2-50	1,562	0.716	Rainfall-triggered landslide	Climate base	250	0.114
Fluvial flood	GFDL-SSP3-50	1,482	0.679	Rainfall-triggered landslide	EC-SSP1-35	247	0.113
Fluvial flood	GFDL-SSP5-50	1,512	0.693	Rainfall-triggered landslide	EC-SSP2-35	256	0.117
Fluvial flood	MPI-SSP1-50	1,786	0.818	Rainfall-triggered landslide	EC-SSP3-35	257	0.118
Fluvial flood	MPI-SSP2-50	2,087	0.956	Rainfall-triggered landslide	EC-SSP5-35	264	0.121
Fluvial flood	MPI-SSP3-50	2,014	0.923	Rainfall-triggered landslide	GFDL-SSP1-35	264	0.121
Fluvial flood	MPI-SSP5-50	1,686	0.773	Rainfall-triggered landslide	GFDL-SSP2-35	262	0.120
Fluvial flood	EC-SSP1-100	1,549	0.710	Rainfall-triggered landslide	GFDL-SSP3-35	261	0.120
Fluvial flood	EC-SSP2-100	1,483	0.679	Rainfall-triggered landslide	GFDL-SSP5-35	250	0.115
Fluvial flood	EC-SSP3-100	1,448	0.664	Rainfall-triggered landslide	MPI-SSP1-35	240	0.110
Fluvial flood	EC-SSP5-100	1,425	0.653	Rainfall-triggered landslide	MPI-SSP2-35	245	0.112
Fluvial flood	GFDL-SSP1-100	1,599	0.733	Rainfall-triggered landslide	MPI-SSP3-35	254	0.116
Fluvial flood	GFDL-SSP2-100	1,543	0.707	Rainfall-triggered landslide	MPI-SSP5-35	250	0.115
Fluvial flood	GFDL-SSP3-100	1,363	0.624	Rainfall-triggered landslide	EC-SSP1-50	258	0.118
Fluvial flood	GFDL-SSP5-100	1,330	0.609	Rainfall-triggered landslide	EC-SSP2-50	265	0.121
Fluvial flood	MPI-SSP1-100	1,940	0.889	Rainfall-triggered landslide	EC-SSP3-50	262	0.120
Fluvial flood	MPI-SSP2-100	1,771	0.812	Rainfall-triggered landslide	EC-SSP5-50	249	0.114
Fluvial flood	MPI-SSP3-100	1,761	0.807	Rainfall-triggered landslide	GFDL-SSP1-50	262	0.120
Fluvial flood	MPI-SSP5-100	1,940	0.889	Rainfall-triggered landslide	GFDL-SSP2-50	268	0.123
Pluvial flood	Climate base	359	0.164	Rainfall-triggered landslide	GFDL-SSP3-50	256	0.117
Pluvial flood	EC-SSP1-35	349	0.160	Rainfall-triggered landslide	GFDL-SSP5-50	241	0.111
Pluvial flood	EC-SSP2-35	340	0.156	Rainfall-triggered landslide	MPI-SSP1-50	254	0.117
Pluvial flood	EC-SSP3-35	336	0.154	Rainfall-triggered landslide	MPI-SSP2-50	235	0.108
Pluvial flood	EC-SSP5-35	341	0.156	Rainfall-triggered landslide	MPI-SSP3-50	229	0.105
Pluvial flood	GFDL-SSP1-35	364	0.167	Rainfall-triggered landslide	MPI-SSP5-50	221	0.101
Pluvial flood	GFDL-SSP2-35	351	0.161	Rainfall-triggered landslide	EC-SSP1-100	231	0.106
Pluvial flood	GFDL-SSP3-35	347	0.159	Rainfall-triggered landslide	EC-SSP2-100	257	0.118
Pluvial flood	GFDL-SSP5-35	349	0.160	Rainfall-triggered landslide	EC-SSP3-100	270	0.124
Pluvial flood	MPI-SSP1-35	394	0.181	Rainfall-triggered landslide	EC-SSP5-100	265	0.121
Pluvial flood	MPI-SSP2-35	421	0.193	Rainfall-triggered landslide	GFDL-SSP1-100	206	0.094
Pluvial flood	MPI-SSP3-35	405	0.186	Rainfall-triggered landslide	GFDL-SSP2-100	271	0.124
Pluvial flood	MPI-SSP5-35	390	0.179	Rainfall-triggered landslide	GFDL-SSP3-100	251	0.115
Pluvial flood	EC-SSP1-50	346	0.158	Rainfall-triggered landslide	GFDL-SSP5-100	264	0.121
Pluvial flood	EC-SSP2-50	344	0.158	Rainfall-triggered landslide	MPI-SSP1-100	206	0.094
Pluvial flood	EC-SSP3-50	332	0.152	Rainfall-triggered landslide	MPI-SSP2-100	191	0.087
Pluvial flood	EC-SSP5-50	333	0.152	Rainfall-triggered landslide	MPI-SSP3-100	248	0.113
Pluvial flood	GFDL-SSP1-50	356	0.163	Rainfall-triggered landslide	MPI-SSP5-100	153	0.070
Pluvial flood	GFDL-SSP2-50	348	0.159				

Figure 24 graphically presents the relative AAL values for all hazards, showing only the baseline climate and those climate scenarios that produce the highest and lowest losses at the portfolio level for each projection year, in the case of climate-sensitive hazards. As shown in Figure 24, the hazard producing the highest AAL at the portfolio level is earthquake, with an AAL of 2.04‰ relative to the total exposed value. This is followed by riverine flooding, with values approximately 55% lower than those associated with seismic hazard. Finally, pluvial flooding and landslides, both earthquake-triggered and rainfall-triggered, exhibit relatively low AAL values.

These results confirm the very high relevance of seismic risk for the canton of Heredia, which is expected given the canton's geographic location within the country, as well as the exposure and vulnerability conditions of its building stock.

Riverine flooding also plays a significant role in the loss profile, with variations that are in some cases notable due to climate change. The drainage network formed by the rivers crossing the city creates substantial risk conditions, combined with the flood vulnerability of buildings. This result may be even more relevant considering that these are highly intervened watersheds with little or no channel maintenance, where obstructions caused by debris and waste frequently reduce drainage capacity.

Finally, pluvial flooding and landslides, whether triggered by earthquakes or rainfall, play a marginal role in the overall building risk profile in Heredia. These hazards are either characterized by very low probabilities of occurrence (as in the case of earthquake-triggered landslides) or by low intensities (as in pluvial flooding) and may therefore be considered negligible in comparison.

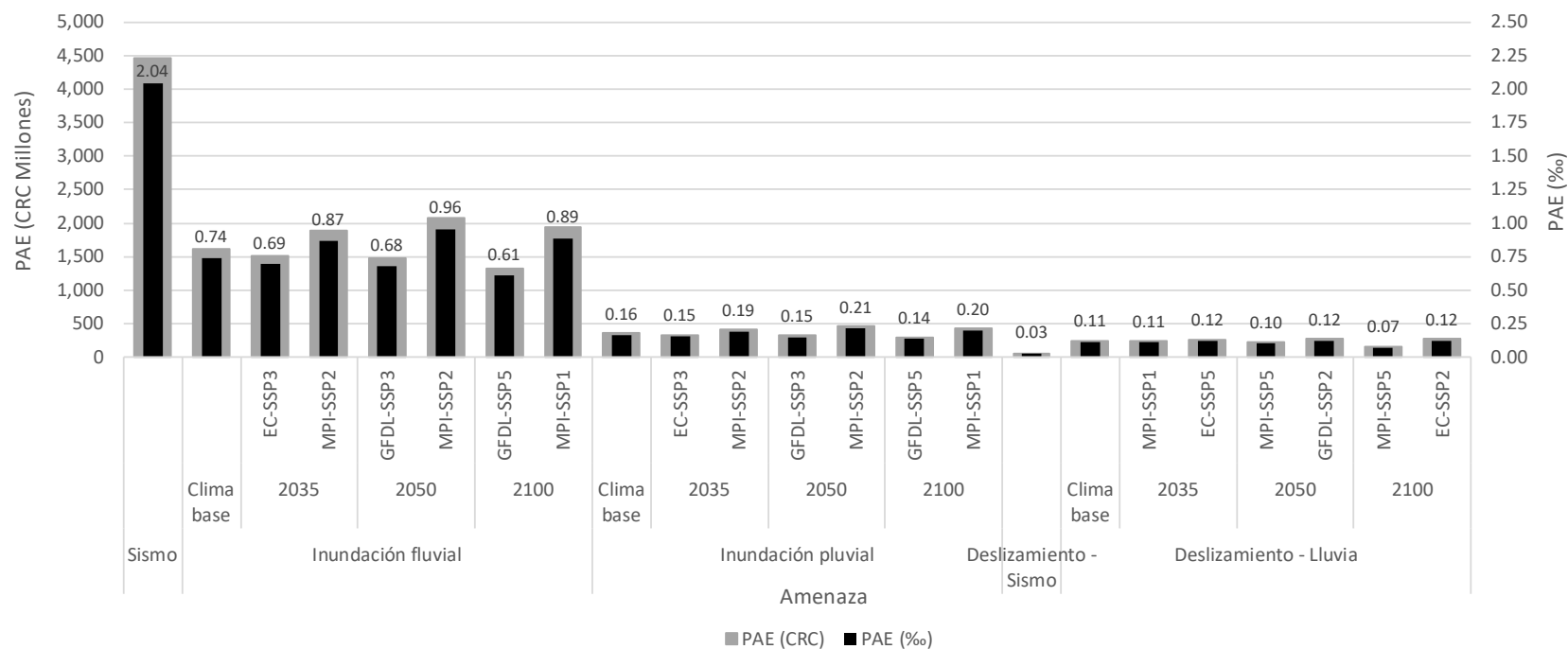


Figure 24. Average Annual Loss by hazard

As explained previously, although Figure 24 presents the complete set of results for earthquake, flooding, and landslide hazards, only the baseline climate and three future climate scenarios are shown for riverine flooding, pluvial flooding, and rainfall-triggered landslides. This is intended to avoid overloading the graphic. However, it is useful to examine the consolidated AAL results for these hazards, including the full set of climate scenarios under which they were evaluated. Figure 25 shows the AAL values as a function of time. Each line in Figure 25 corresponds to a different climate projection, that is, a specific combination of GCM and emission pathway. This allows visualization of the temporal evolution of riverine flood risk under different climate models. Figure 26 presents the same information for pluvial flooding, and Figure 27 for rainfall-triggered landslides.

As observed, although AAL values fluctuate across the projection years considered, these variations do not follow a strictly increasing trend over time, nor do they systematically increase with higher emission pathways. In other words, risk does not necessarily grow with higher emissions, nor does it inevitably increase toward the future. This behavior is entirely normal and expected, as the relationship between greenhouse gas emissions and risk is highly nonlinear. Higher emissions do not automatically imply higher risk. The resulting losses depend on the specific interaction between hazard characteristics, exposure, and vulnerability, which mediate how hydrometeorological phenomena translate into economic impacts under each climate condition analyzed.

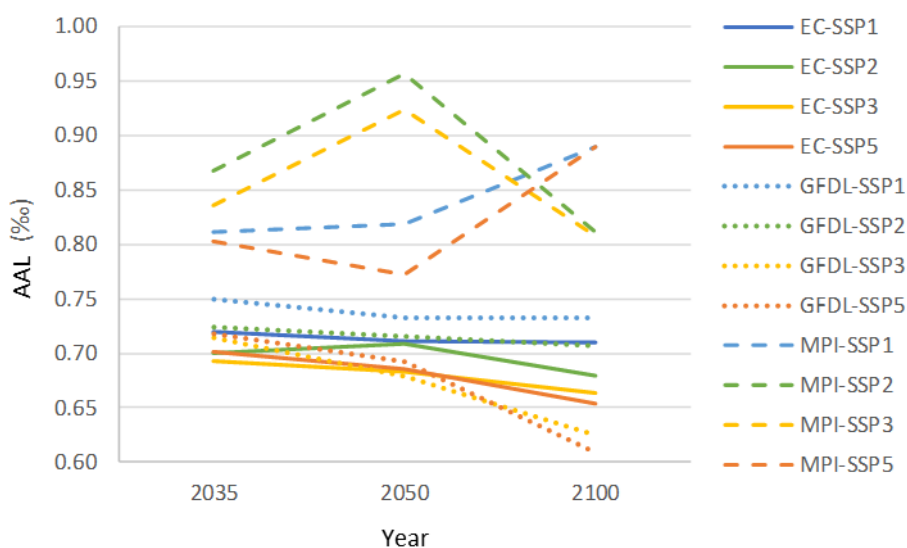


Figure 25. Average Annual Loss due to fluvial flood for the considered climate change scenarios

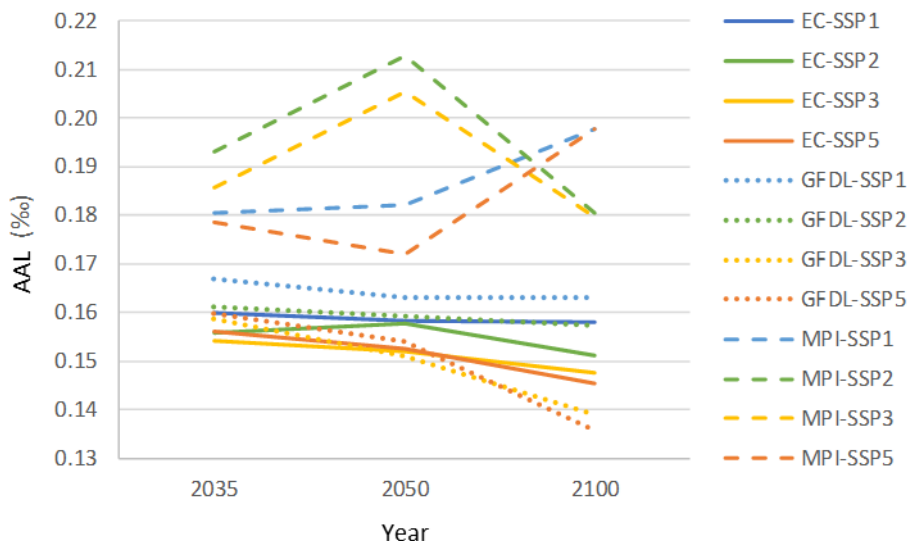


Figure 26. Average Annual Loss due to pluvial flood for the considered climate change scenarios

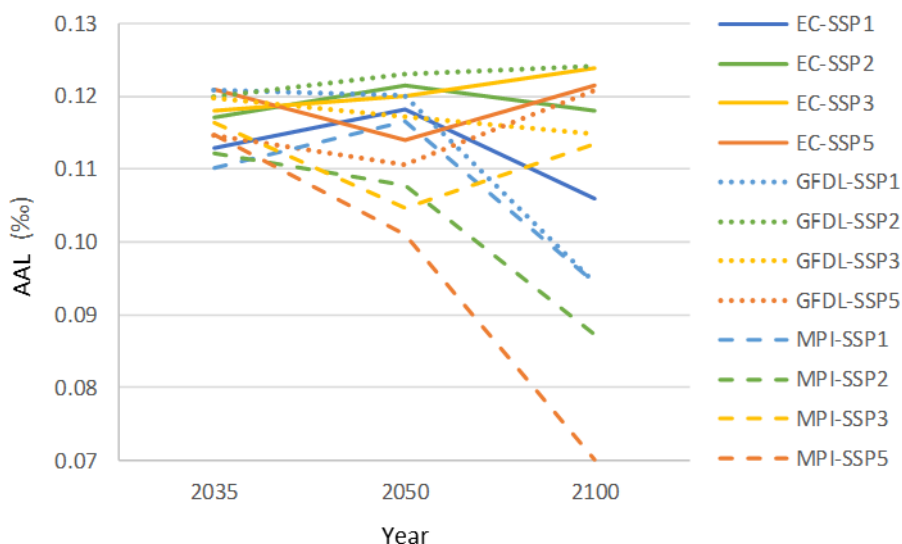


Figure 27. Average Annual Loss due to rainfall-triggered landslides for the considered climate change scenarios

Figure 25, Figure 26 and Figure 27 illustrate the very high level of uncertainty inherent in risk modeling that incorporates climate change projections. Each line shown represents a possible trajectory of change in risk. However, it is impossible to determine which of these trajectories will materialize in the future, or even whether the actual risk in 2035, 2050, or 2100 will fall within the range of projections analyzed. This condition is known as deep uncertainty, as defined in Section 5.5 of the Inception Report. When risk is

addressed under deep uncertainty, point estimates—such as AAL—are transformed into interval-based metrics, meaning they are inherently imprecise.

For imprecise risk metrics, it is not possible to establish a probability distribution within the interval of variation; only the upper and lower bounds of that interval can be identified. As shown in Figure 25, Figure 26 and Figure 27, the maximum and minimum AAL values for each projection year—arising from different combinations of GCMs and emission pathways—represent the bounds of the metric for those years.

These bounds define the range of variation of AAL, and this interval itself evolves over time, in accordance with projected changes in greenhouse gas concentrations across the different emission pathways considered.

In the case of flooding, both riverine and pluvial, the temporal variation of AAL for the Heredia building portfolio shows differentiated behavior depending on both the global circulation model (GCM) and the emission pathway considered. For the EC model, the curves exhibit a generally smooth decreasing trend over time across all SSP scenarios, with gradual reductions from 2035 to 2100. This decrease is more pronounced under higher-emission scenarios (SSP3 and SSP5), suggesting a progressive reduction in expected annual losses under the hydrological projections associated with this model. For the GFDL model, AAL remains relatively stable under SSP1 and SSP2, with only minor temporal variations. Under SSP3 and SSP5, however, a more marked decrease toward 2100 is observed, indicating greater sensitivity of the results to high-emission pathways over longer time horizons.

In contrast, the MPI model displays a non-monotonic evolution. Under SSP2 and SSP3, AAL increases from 2035 to 2050 and then decreases toward 2100. Under SSP1 and SSP5, AAL tends to increase toward the end of the century, reaching values comparable to or even exceeding those observed mid-century. Overall, comparison across models shows that the temporal signal of AAL is not uniform. In several cases, differences between models are of the same order of Magnitude as differences between emission scenarios. This reflects the combined influence of the assumed climate trajectory and the hydrological response characteristics inherent to each global model.

In the case of rainfall-triggered landslides, the temporal variation of AAL shows patterns different from those observed for flooding, with greater long-term divergence across emission scenarios. For the EC model, AAL values tend to increase slightly from 2035 to 2050 in most scenarios, followed by stabilization or a slight reduction toward 2100, with relatively limited differences among SSP pathways. The GFDL model exhibits contrasting behavior: while most scenarios remain stable or slightly increasing over time, the SSP1 scenario shows pronounced reductions toward the end of the century. The MPI model displays the greatest temporal range, with progressive decreases in AAL under SSP2 and SSP5 toward 2100, whereas SSP3 shows an increase after 2050. These inter-model and inter-scenario differences reflect the high sensitivity of landslide risk to the representation of extreme precipitation and its temporal evolution in climate models, as well as to the way these signals are translated into the probability of slope instability activation.

5.1.2 Probable Maximum Loss (PML)

As mentioned in Section 2.3.2, PML curves are an alternative way of presenting loss exceedance curves. They provide a complete representation of portfolio risk, incorporating both frequent events with relatively small losses and catastrophic events with very low frequency of occurrence. The PML curve format, expressed in terms of return period, allows for clearer communication of the level of risk associated with events across the full frequency spectrum, from very frequent events to rare, low-probability events.

Figure 28 presents the PML curves for all hazards and climate scenarios considered in this assessment. In these graphs, PML is expressed in relative terms, as a percentage of the total exposed value. The curves illustrate the increasing nature of loss as a function of return period, that is, losses increase as events become less frequent. Two general types of behavior can be observed in the PML curves: i) curves with slow growth over increasing return periods and no clear tendency toward stabilization, typical of hazards such as earthquakes and landslides; and ii) curves with rapid growth at short return periods and clear stabilization, approaching nearly constant values at long return periods, typical of hazards such as riverine and pluvial flooding.

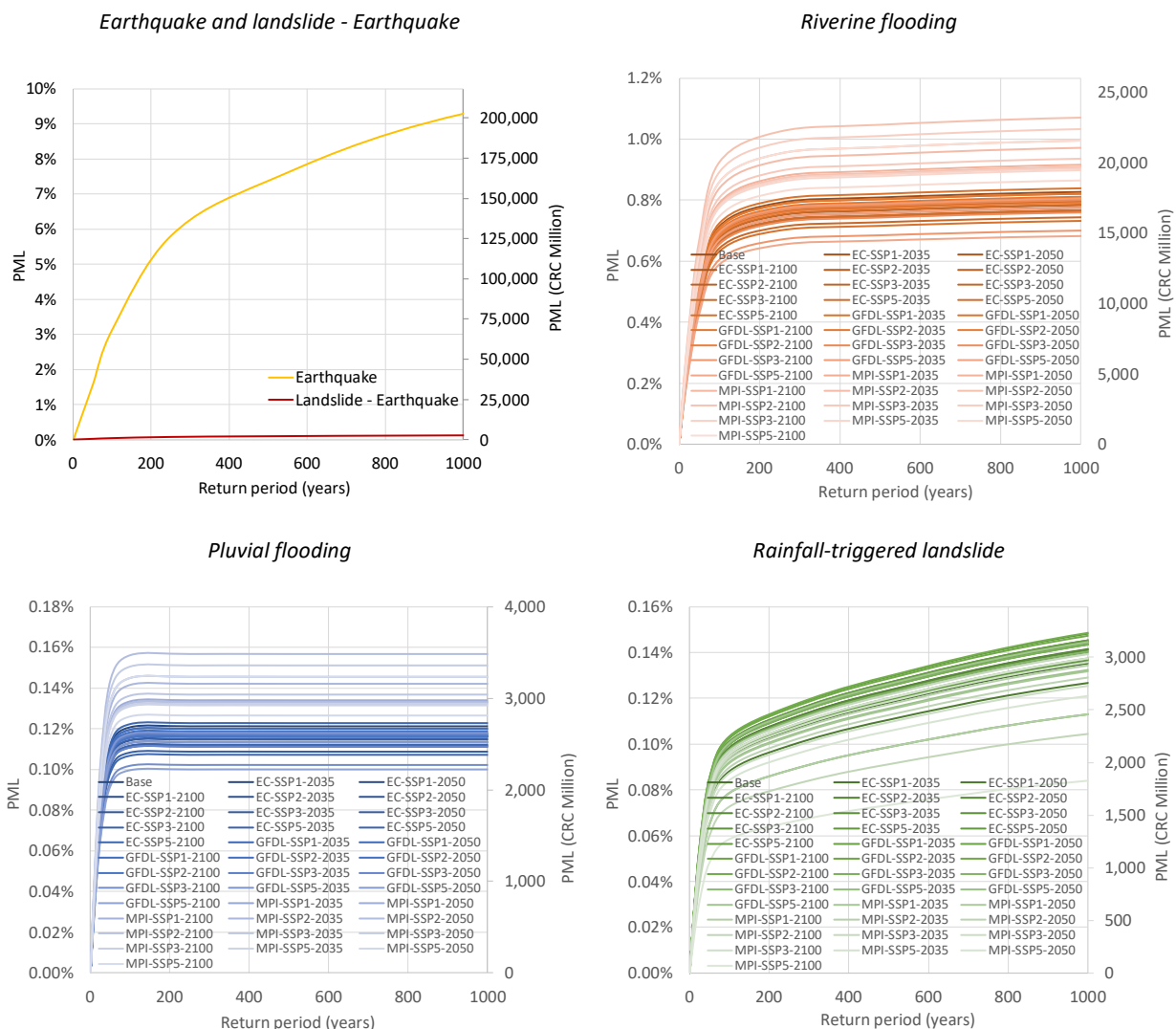


Figure 28. PML Curves for all considered hazards and all climate scenarios

Figure 29 presents a comparison of the PML curves for all hazards, showing only the climate scenarios that produce the highest AAL in each future projection year for riverine and pluvial flooding, as well as for rainfall-triggered landslides. This approach is adopted because including all results for the 36 future climate scenarios considered for these hazards in a single graph would not allow for an appropriate comparison.

The comparison of the PML curves illustrates the characteristic shape of each curve, which, as previously noted, depends on the frequency of event occurrence. It is evident that earthquakes are the hazard producing the highest PML values at long return periods, clearly exceeding the other hazards. This implies that earthquakes have the capacity to correlate losses across multiple locations simultaneously, thereby generating large aggregated losses for low-frequency (long return period) events. It can also be observed that riverine flooding, under any of the climate scenarios considered, does not reach loss levels as high as

those associated with earthquakes at long return periods, but shows similar Magnitudes at short return periods. In other words, for relatively frequent events, flood risk is comparable to seismic risk. This distinction is important because risk reduction measures implemented through public policy will affect these loss levels differently depending on the return period considered. Strategies aimed at reducing frequent, moderate losses may differ substantially from those designed to mitigate rare, catastrophic events.

It can also be concluded that, for long return periods, pluvial flooding generates losses of similar Magnitude to those caused by landslides. This means that extreme events associated with these hazards may result in comparable loss amounts under current exposure and vulnerability conditions. However, these hazards produce comparatively lower overall risk levels and may be considered marginal from a portfolio-level perspective.

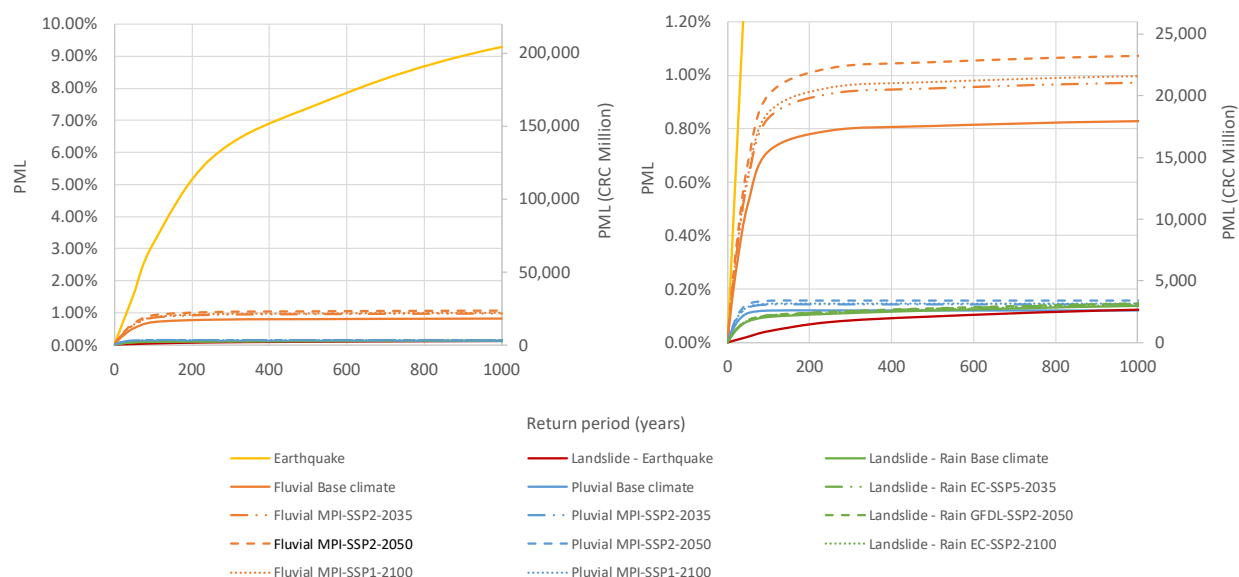


Figure 29. Left image: comparison of PML curves for the considered hazards and selected climate scenarios. Right image: enlargement of the left image.

5.1.3 Results by Location

The results presented above are useful for quantifying building risk in the canton of Heredia from a portfolio perspective, supporting sector-level risk management decisions and the design of financial protection instruments aimed at covering the entire portfolio. However, portfolio-level results do not illustrate the risk faced by each individual building. For each of the 36,110 buildings included in the

exposure database, risk is evaluated in terms of AAL. Only AAL is presented, as it is the only risk metric that can be disaggregated at the individual location level³.

Figure 30 through Figure 34 present maps showing the spatial distribution across the canton of AAL (expressed per thousand, %, relative to the exposed value of each building) for all buildings included in the assessment. For a better visualization of the distribution of losses in the canton, the selection of color ranges differs in each figure according to the maximum loss levels reached for each hazard, seeking to graphically maximize the differences between the ranges.

To limit the length of this document, AAL results are presented for all hazards, but only under the baseline climate for climate-sensitive hazards. The full set of results is included in the project dataset. Buildings are shown as the polygons delineating their respective property lots.

³ Although it is mathematically possible to disaggregate PML by location, the uncertainty associated with such estimates is too high; therefore, this disaggregation is not performed. Portfolio-level PML, in contrast, benefits from a reduction in overall uncertainty as a result of the law of large numbers, since it aggregates many exposed elements into a single result. For this reason, PML is reported only at the portfolio level.

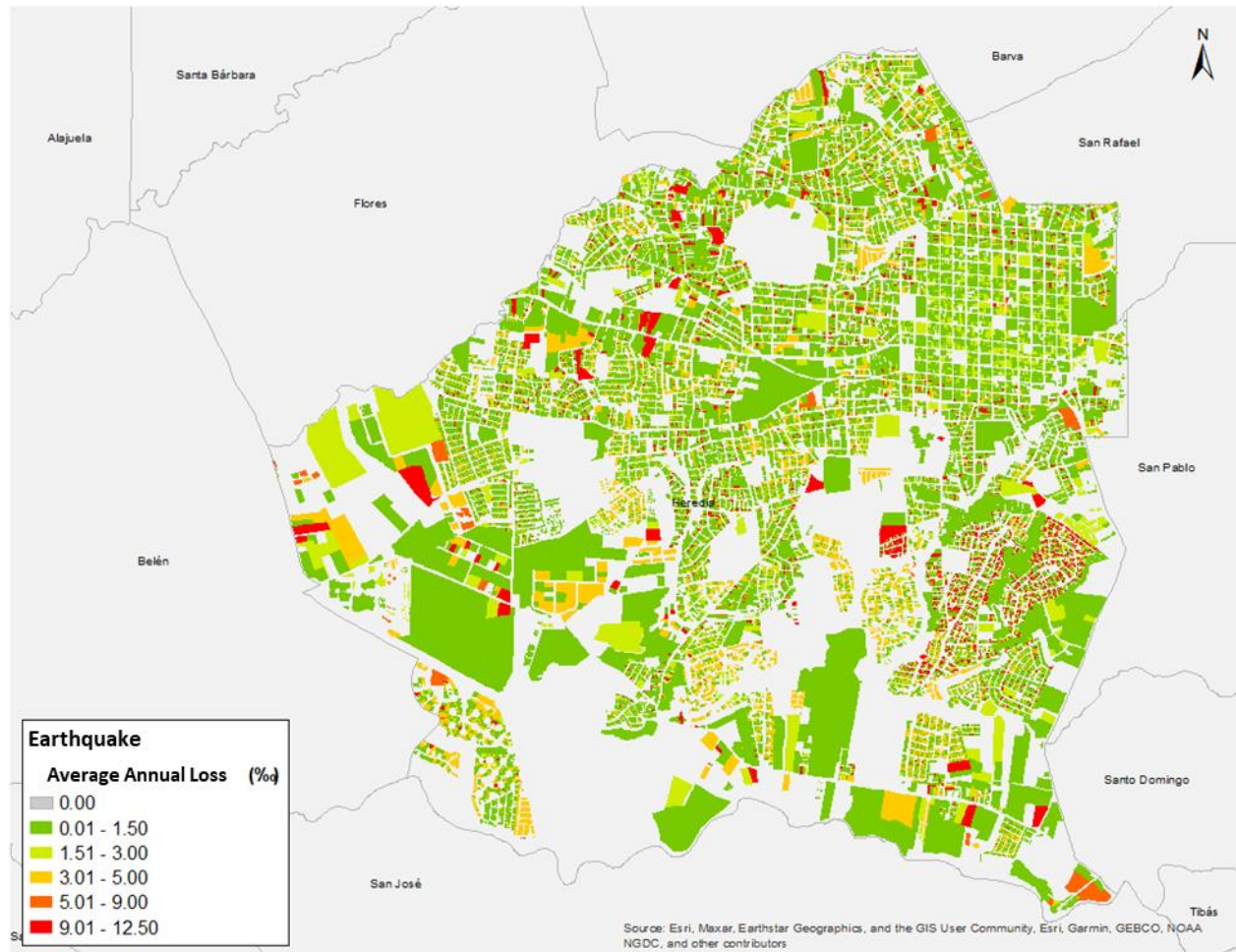


Figure 30. Average Annual Loss due to earthquakes for buildings in the canton of Heredia

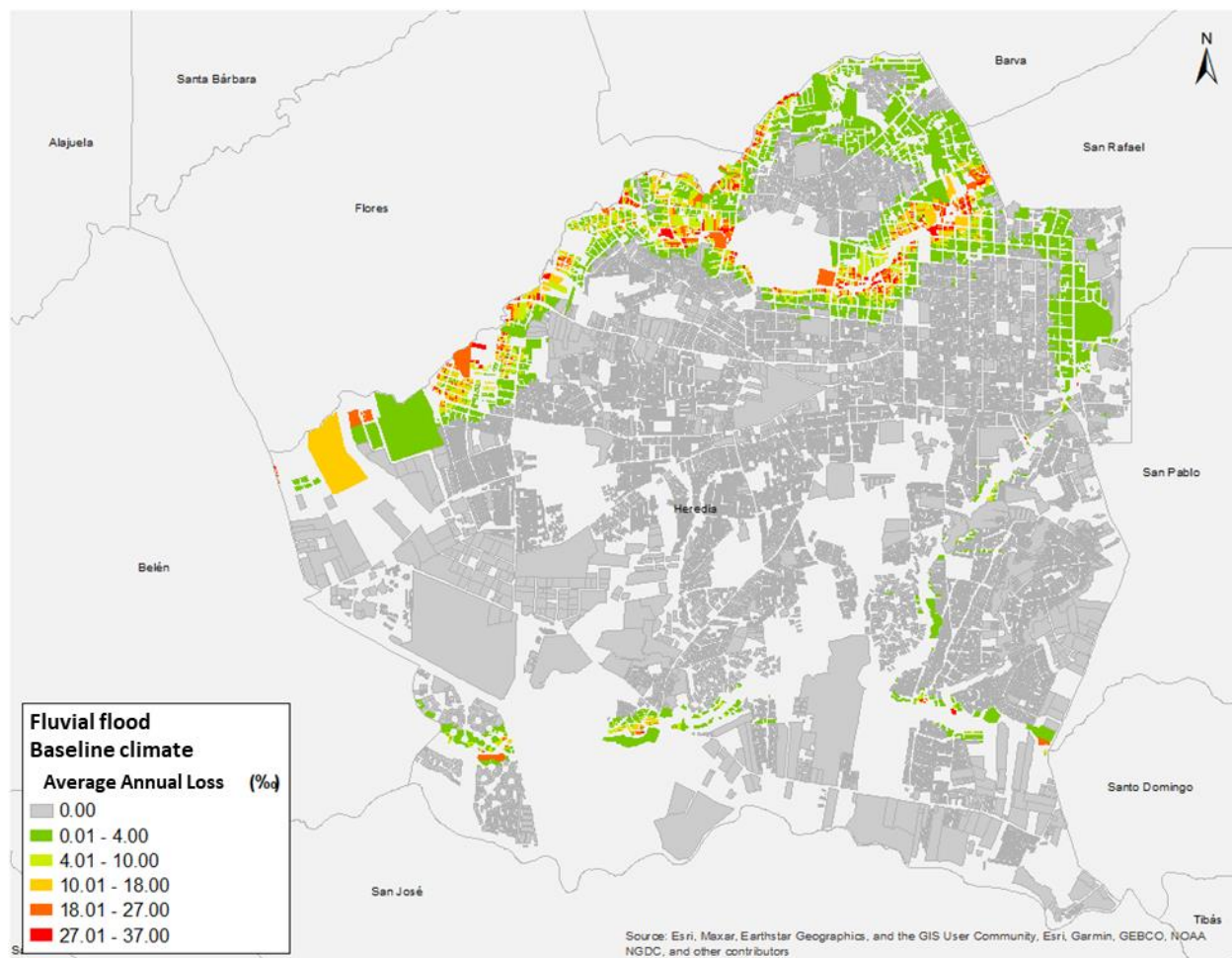


Figure 31. Average Annual Loss due to fluvial flood (Baseline climate) for buildings in the canton of Heredia

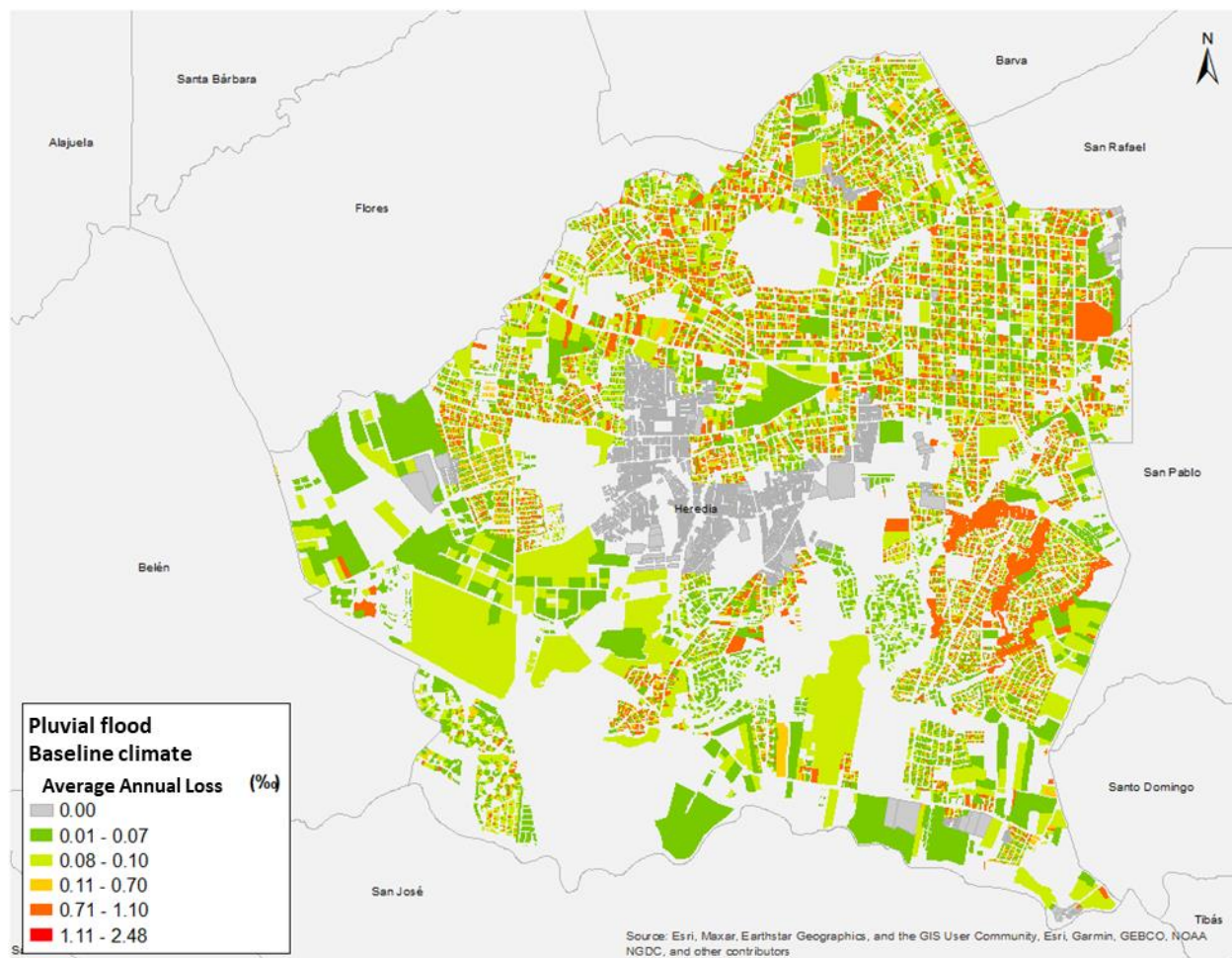


Figure 32. Average Annual Loss due to pluvial flood (Baseline climate) for buildings in the canton of Heredia

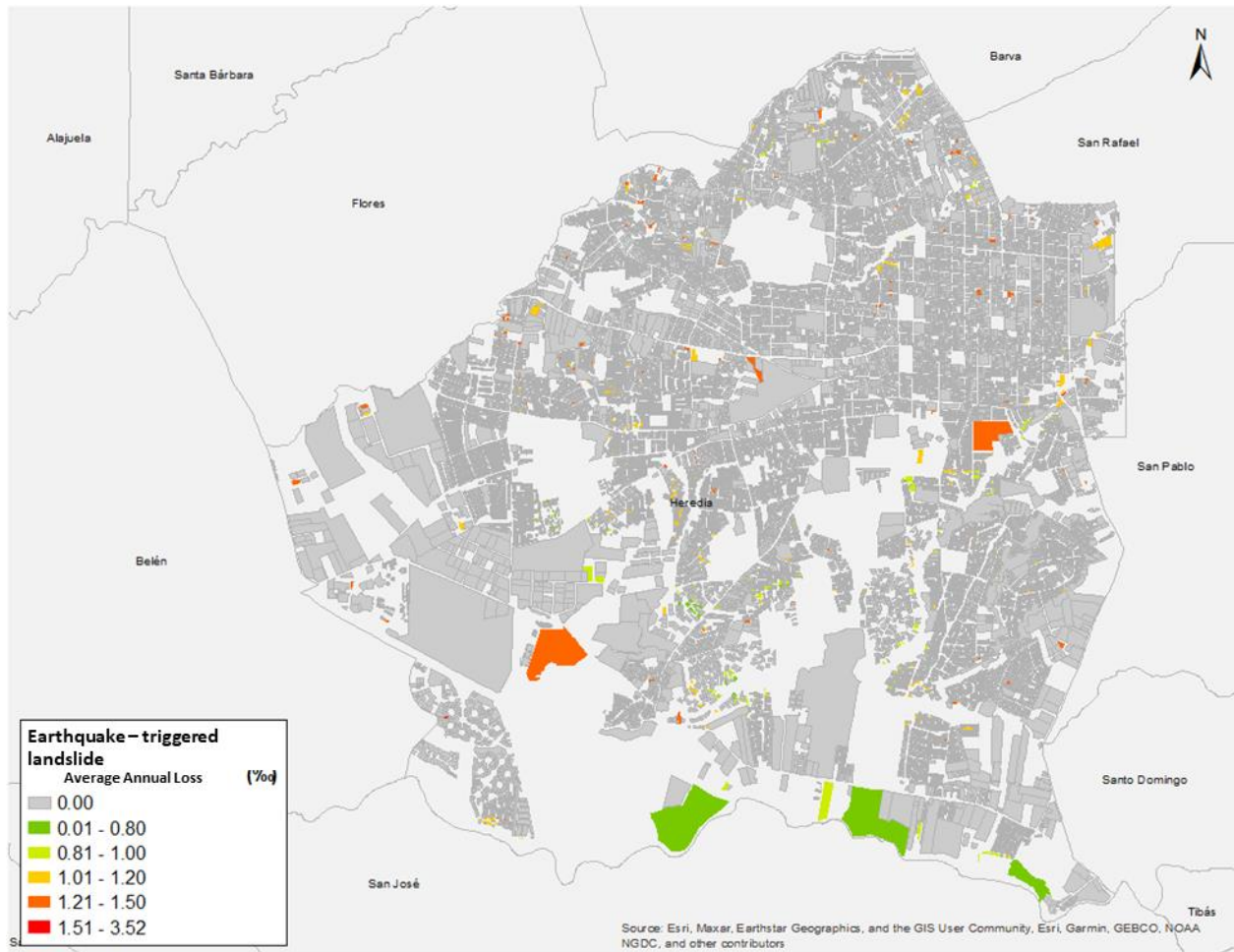


Figure 33. Average Annual Loss due to earthquake-triggered landslide for buildings in the canton of Heredia

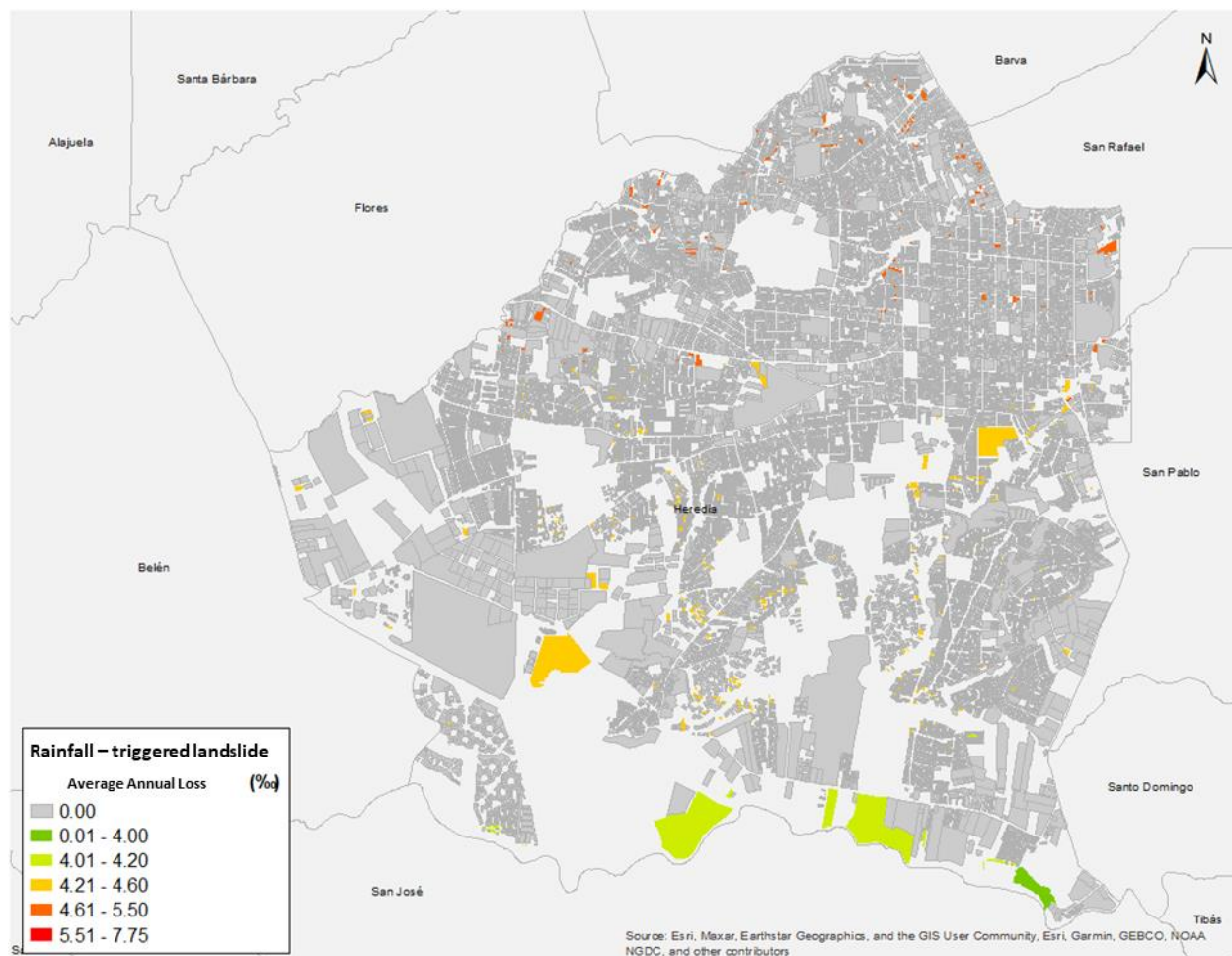


Figure 34. Average Annual Loss due to rainfall-triggered landslide (baseline climate) for buildings in the canton of Heredia

As observed, the loss distributions differ significantly among the hazards considered, which is expected. For example, earthquake (Figure 30) clearly generates higher loss correlation, as it is a hazard capable of affecting 100% of the building portfolio. The entire territory is exposed, to some degree, to seismic events. This explains the very high PML values obtained compared to other hazards. However, when examining point values for individual buildings, the maximum AAL for earthquake is 12.50‰, which is lower than the highest point loss recorded for riverine flooding, the hazard that presents the highest risk at the individual building level (37‰).

The maximum point AAL values for the other hazards are as follows: 2.48‰ for pluvial flooding, 3.52‰ for earthquake-triggered landslides, and 7.75‰ for rainfall-triggered landslides. For hazards influenced by climate change, the values reported correspond to the baseline climate.

The above illustrates that, although earthquakes correlate losses across many locations in each event, thus generating one of the most significant risk levels at the portfolio scale, the losses experienced individually by each building are highly heterogeneous. There are locations where other hazards may be far more critical, in risk terms, than earthquakes. The maps presented show areas strongly affected by riverine flooding (Figure 31), as well as other locations with considerable risk levels due to landslides (Figure 33 and Figure 34). These hazards do not correlate losses across a large number of elements in a single event. However, they may have a strong impact on individual assets in specific locations, where potentially high intensity combined with high vulnerability results in elevated AAL values.

The results presented are inevitably governed by the frequency-severity relationship inherent to each hazard. Earthquakes are capable of producing very large impacts in individual events, but with low frequency of occurrence. This contrasts with phenomena such as flooding, whose impacts at the individual event level are generally smaller but occur more frequently. This dynamic explains the relative loss patterns observed among these hazards and across all those considered in this study.

Analyzing losses at the individual element level is particularly important for other risk management processes, especially those focused on local and asset-specific mitigation of vulnerability, modification of exposure (such as infrastructure relocation), and the evaluation of potential hazard mitigation works (for example, riverine flood protection measures). These data complement the aggregated risk results by providing a more detailed understanding of how losses are spatially concentrated and where targeted interventions would be most effective in reducing vulnerability.

5.1.4 Affected Population

The impact on the population is approximated based on the losses assessed in this study. This represents a general and approximate estimation, in which no distinction is made between the type of impact or its severity, as the required information is not available and such differentiation is not the objective of this work.

The affected population is determined as a proportion of the Potentially Affected Population (PAP). This proportion corresponds to the relative Average Annual Loss (AAL) evaluated at the building level (and aggregated across all hazards). This results in a rough estimate of the Average Annual Affected Population (AAP). Although this is a coarse approximation, given that no additional elements are available for its determination, it is considered acceptable and sufficient to provide an indication of the order of Magnitude of the population impact. The assessment can be summarized by the following equation:

$$AAP = PAP \cdot AAL \quad \text{Equation 11}$$

Where AAL is the relative expected annual loss, corresponding to the total aggregated across all hazards. The Potentially Affected Population (PAP) corresponds to the total population of the canton, but distributed by use sectors, as defined in the exposure model. Table 9 shows the exposed population (PAP) by use sector, and the affected population (AAP) for each hazard considered in Heredia.

Table 9. Affected Population by Use Sector for the Considered Hazards

Sector	Potential Affected Population (PAP)	Affected Annual Average (AAA)				
		Earthquake	Fluvial flood (Climate base)	Pluvial flood (Climate base)	Earthquake-triggered landslides	Rainfall-triggered landslides (Base climate))
Residential	135,149	282	134	30	4	16
Health	134	0	0	0	0	0
Education	1,577	2	1	0	0	1
Institutional	1,871	3	0	0	0	0
Commercial	10,643	23	5	1	0	1
Total	149,374	310	140	31	4	18

5.2 Infrastructure Portfolio

Within the Strategic Project for Heredia, multiple critical infrastructure sectors were included in order to cover those defined by Decree No. 42465 of 2020 for Costa Rica. These include the following sectors: road (highway), rail, energy (electric power), telecommunications, hydrocarbons, as well as water supply and sewerage systems, applied within the scope of the canton of Heredia.

Each sector is composed of several portfolios according to its nature. Table 10 presents a general summary with the total estimated replacement value and the total number of individual elements that make up each sector considered.

Table 10. Economic Valuation and Infrastructure Exposure Elements in the Canton of Heredia

Sector	Economic Value (€)	Elements
Road	119,590,241,400	340.5 km of roads
		12 national-level bridges and 37 municipal-level bridges
Rail	986,648,800	4.9 km of railway lines
Electric Power	45,521,947,100	2 power generation plants (hydropower)
		6 substations
		108 high-voltage transmission towers
		48.7 km of high-voltage circuits (transmission)
		2,596 medium- and low-voltage transformers
		11,814 distribution poles
		1,027.3 km of medium- and low-voltage circuits (distribution)
Telecommunications	2,230,418,300	110 telecommunications towers
Hydrocarbons	3,743,233,900	12.2 km of pipeline
Drinking Water	43,000,332,900	28 drinking water sources
		53 storage tanks
		17 pumping systems
		568.4 km of supply network
Wastewater	13,542,726,700	924 hydrants
		160.3 km of collector network
		2,317 manholes
		6 water treatment plants

The results are presented below in terms of the risk metrics used in this study (AAL and PML) for the different sectors considered.

5.2.1 Road Sector

5.2.1.1 Average Annual Loss (AAL)

Table 11 presents the AAL values by climate scenario for the road sector, this AAL values reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided. In order to limit the length of the document, only the baseline climate and the climates that produce the maximum and minimum AAL for hydrometeorological hazards are presented. Figure 35 shows the same information graphically.

Table 11. Average annual loss by hazard and climate scenario in the road sector. Values in millions of Costa Rican colones (CRC).

Portfolio		Roads		Bridges	
Exposed value		\$ 98,625,227,300		\$ 20,965,014,100	
Hazard	Scenario	AAL	AAL (‰)	AAL	AAL (‰)
Earthquake		\$ 18,227,206	0.18	\$ 27,786,939	1.33
Fluvial flood	Base	\$ 38,438,053	0.39	\$ 27,824,657	1.33
	Min. 2035	\$ 36,023,172	0.37	\$ 26,082,061	1.24
	Max. 2035	\$ 45,128,691	0.46	\$ 32,648,771	1.56
	Min. 2050	\$ 35,321,270	0.36	\$ 25,575,424	1.22
	Max. 2050	\$ 49,753,319	0.50	\$ 35,979,888	1.72
	Min. 2100	\$ 31,697,053	0.32	\$ 22,958,448	1.10
	Max. 2010	\$ 46,237,806	0.47	\$ 33,447,917	1.60
Pluvial flood	Base	\$ 112,354	0.00	\$ -	0.00
	Min. 2035	\$ 105,061	0.00	\$ -	0.00
	Max. 2035	\$ 132,720	0.00	\$ -	0.00
	Min. 2050	\$ 102,948	0.00	\$ -	0.00
	Max. 2050	\$ 146,946	0.00	\$ -	0.00
	Min. 2100	\$ 92,080	0.00	\$ -	0.00
	Max. 2010	\$ 136,121	0.00	\$ -	0.00
Earthquake-triggered landslides		\$ 7,326,326	0.07	\$ 4,389,620	0.21
Rainfall triggered landslides	Base	\$ 25,902,839	0.26	\$ 14,060,378	0.67
	Min. 2035	\$ 25,805,109	0.26	\$ 14,084,657	0.67
	Max. 2035	\$ 29,009,917	0.29	\$ 15,150,853	0.72
	Min. 2050	\$ 25,340,984	0.26	\$ 12,551,225	0.60
	Max. 2050	\$ 28,959,280	0.29	\$ 15,995,595	0.76
	Min. 2100	\$ 25,041,197	0.25	\$ 10,132,151	0.48
	Max. 2010	\$ 32,994,707	0.33	\$ 13,467,569	0.64

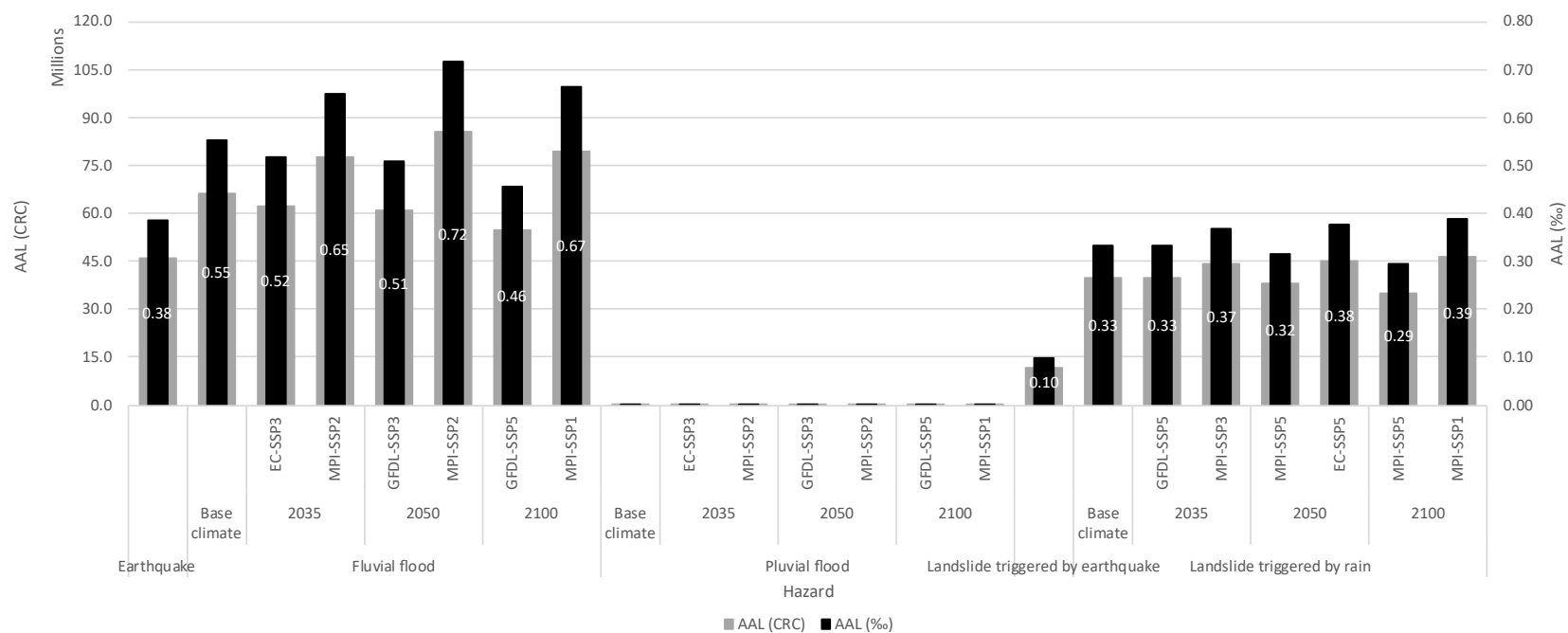


Figure 35. Average Annual Loss by Hazard for the Road Sector

The AAL results for the road sector in Heredia show a clear differentiation between the components of the road and bridge portfolios, both in absolute Magnitude and in relative loss. For roads, hydrometeorological hazards associated with fluvial flooding and rainfall-triggered landslides concentrate the highest AAL values, with losses on the order of CRC 38–50 million for fluvial flooding and CRC 26–33 million for rainfall-triggered landslides, depending on the climate scenario considered. In contrast, seismic risk presents a lower AAL, close to CRC 18.2 million, while earthquake-triggered landslides contribute additional but more moderate values (~CRC 7.3 million). Pluvial flooding, in turn, is practically marginal in terms of expected losses, with values below CRC 0.15 million, indicating a very small contribution within the overall annual loss balance.

In the case of bridges, relative losses are consistently higher, reflecting greater structural and functional sensitivity within this subsector. Both earthquakes and fluvial flooding show comparable AAL values under the baseline scenario, around CRC 27–28 million, corresponding to relative losses on the order of 1.3‰ of the exposed value. Likewise, rainfall-triggered landslides generate significant expected losses (~CRC 14–16 million), while earthquake-triggered landslides represent a smaller contribution (~CRC 4.4 million). Overall, the range of climate variation considered introduces noticeable dispersion in fluvial and rainfall-induced landslide hazards, with increases toward maximum scenarios (2050 and 2100), which is reflected in a widening of the annual AAL range under future conditions.

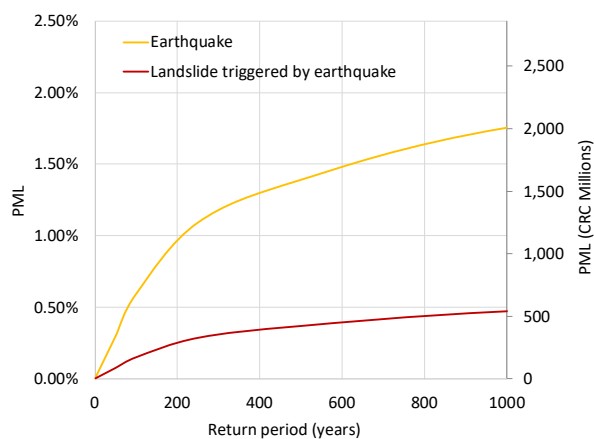
5.2.1.2 Probable Maximum Loss (PML)

Figure 36 shows the PML curves for the road sector. Pluvial flooding is not included because it does not generate losses in this portfolio.

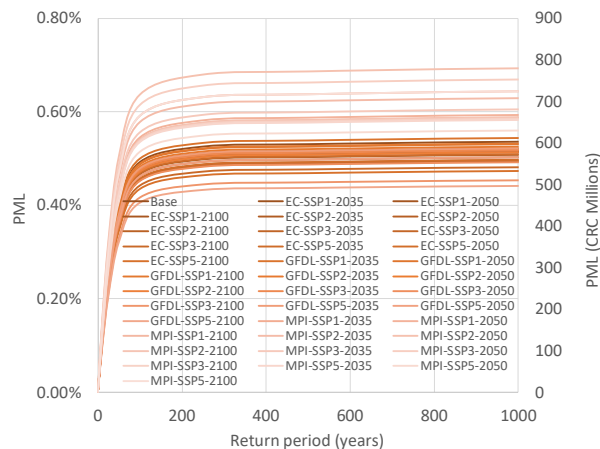
The PML curves presented for the road sector allow the characterization of loss behavior in the low-frequency–high-severity domain, differentiating both the nature of each hazard and the influence of the multiple climate scenarios considered. In the case of earthquakes and earthquake-triggered landslides, the curves display a typical heavy-tailed hazard pattern, with marked increases in losses toward longer return periods, highlighting the role of infrequent extreme events in defining aggregate risk. This behavior is particularly relevant for bridges, where the relative annual loss is already high and where extreme scenarios dominate the upper portion of the exceedance curves.

For fluvial flooding and rainfall-triggered landslides, the presence of multiple overlapping curves in each graph corresponds to the inclusion of the 36 alternative climate scenarios modeled. The dispersion among curves is more evident for fluvial flooding, where maximum future scenarios tend to shift the distribution toward higher losses at different exceedance levels. For rainfall-triggered landslides, significant climatic variability is also observed, although with different slopes and separations, suggesting sensitivity both to changes in hydrometeorological intensity and to the spatial distribution of exposure.

Earthquake and landslide triggered by earthquake



Fluvial flood



Landslide triggered by rain

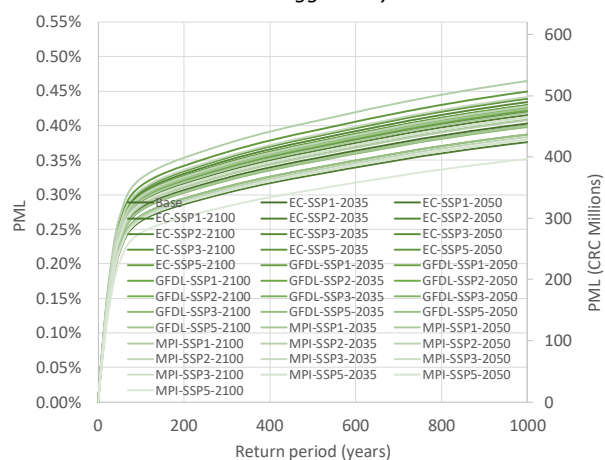


Figure 36. PML Curves for all considered hazards and all climate scenarios – Road sector

5.2.1.3 Losses by location

Figure 37 to Figure 40 present the maps of AAL by individual sector elements for the hazards considered. Pluvial flooding is not included, as it does not generate losses in this portfolio.

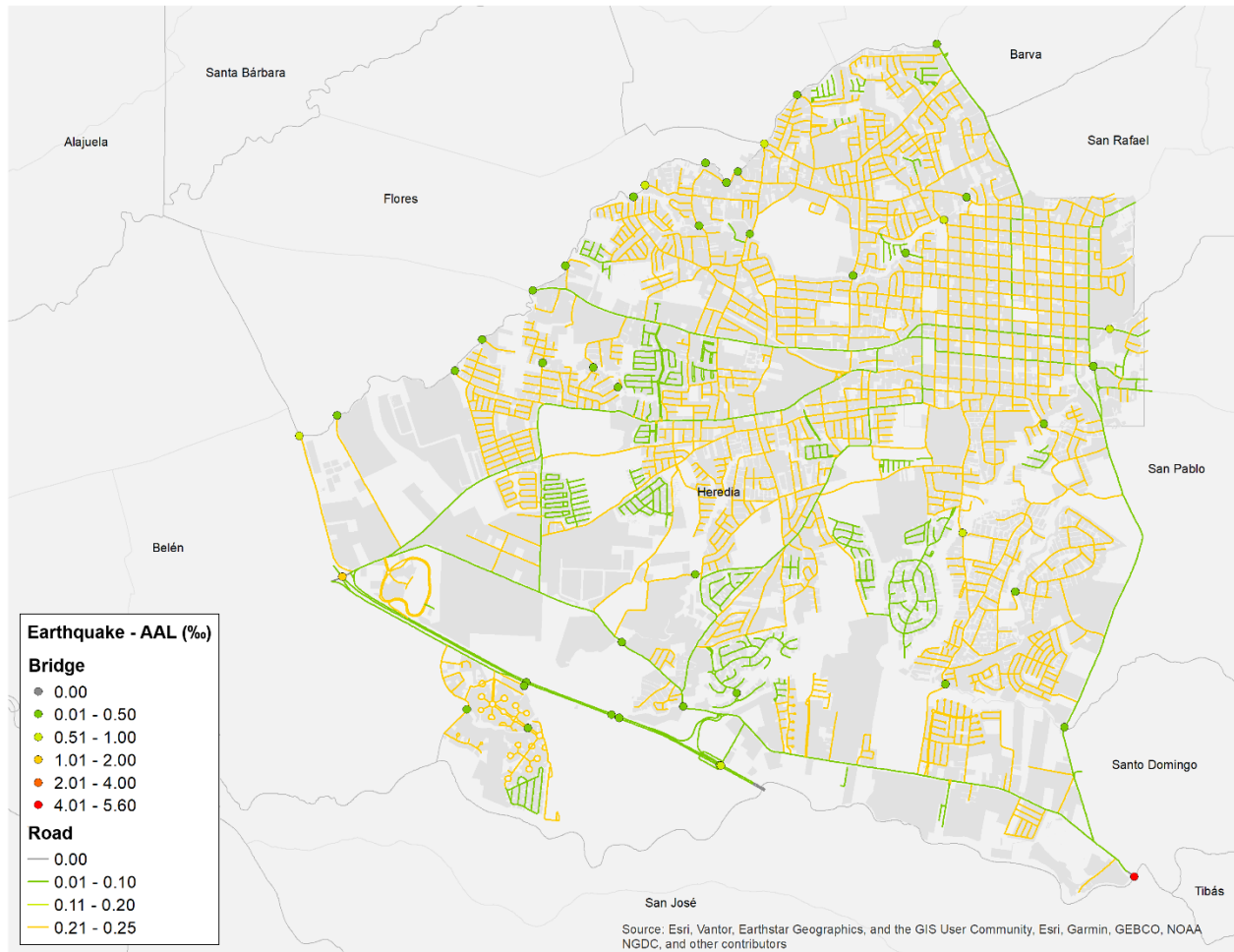


Figure 37. Average Annual Loss due to earthquakes for the road sector in the canton of Heredia

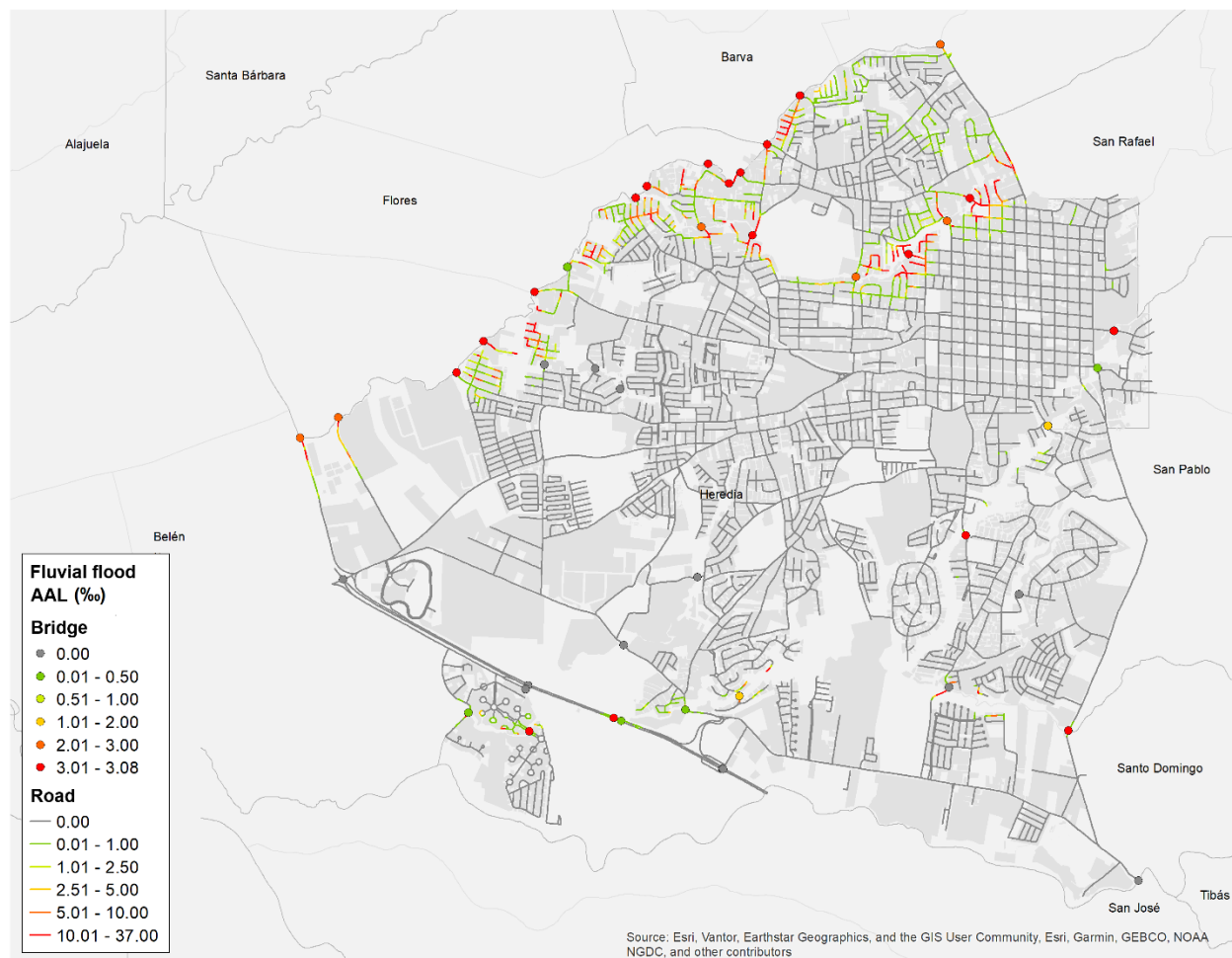


Figure 38. Average Annual Loss due to fluvial flood for the road sector in the canton of Heredia

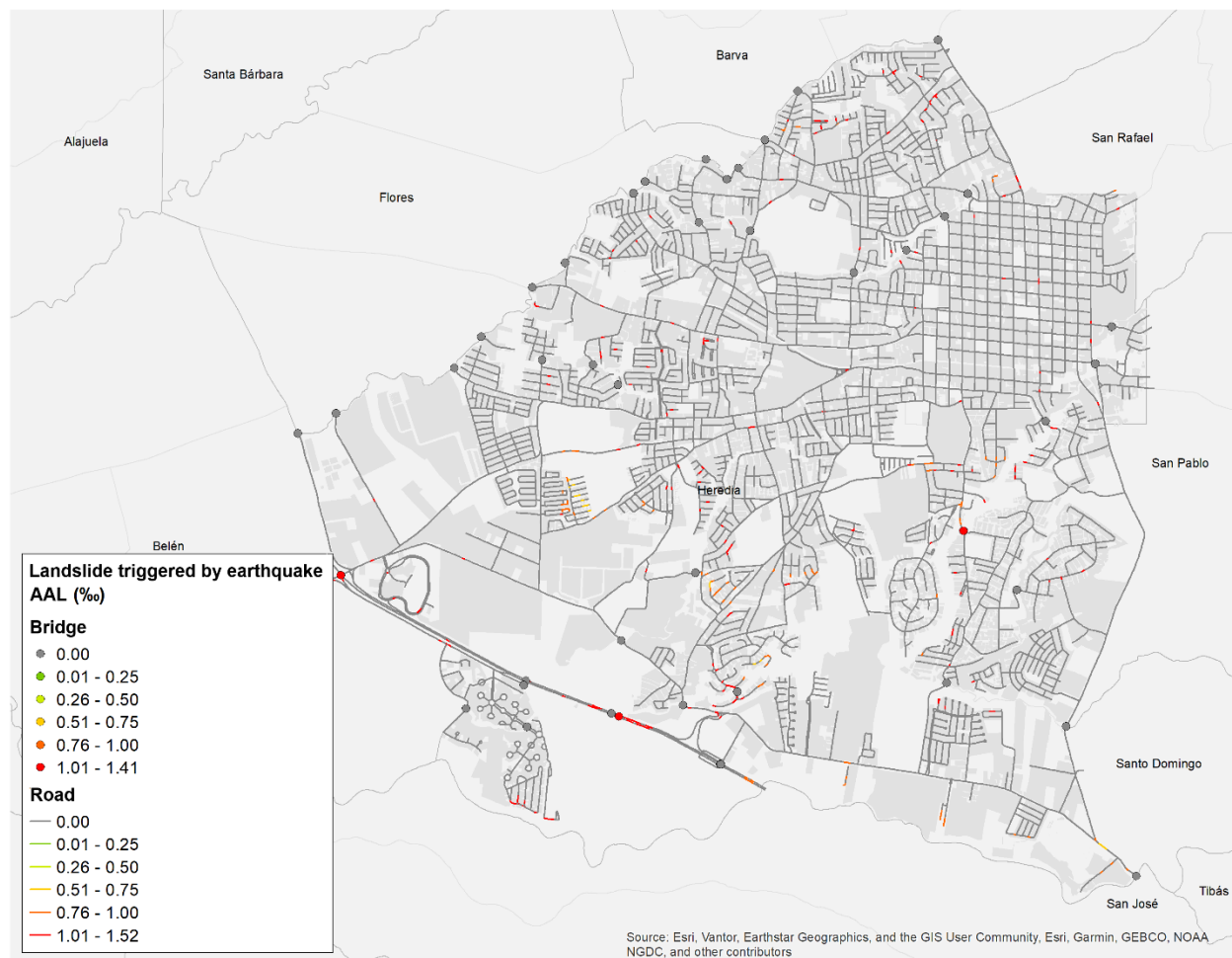


Figure 39. Average Annual Loss due to earthquake-triggered landslides for the road sector in the canton of Heredia

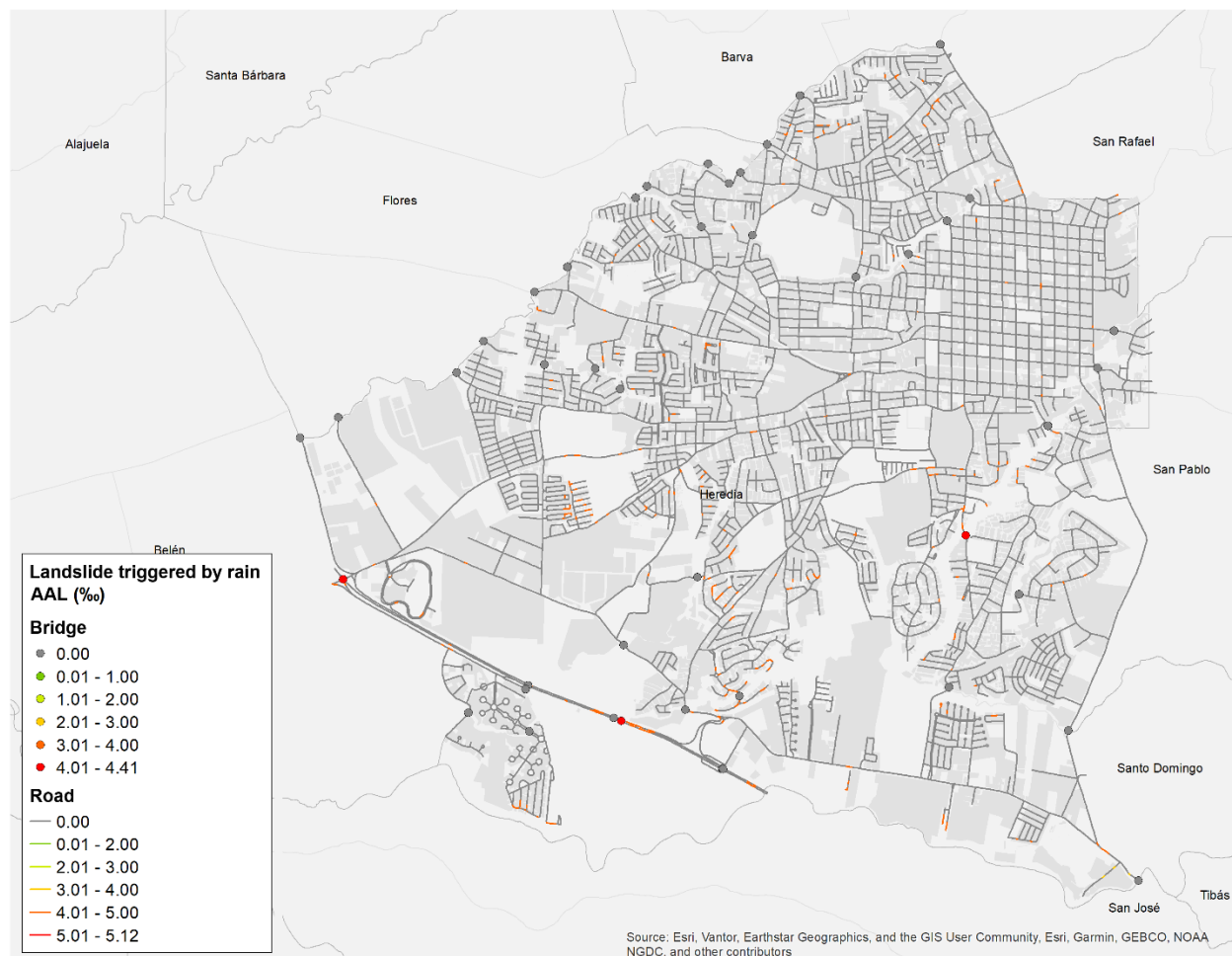


Figure 40. Average Annual Loss due to rainfall-triggered landslides for the road sector in the canton of Heredia

The AAL maps by location (Figure 27) show that risk is not distributed homogeneously across the canton's road network but instead concentrates in specific segments where high hazard conditions and critical exposure converge. In the case of earthquakes, the expected losses tend to be organized according to the spatial distribution of the most vulnerable infrastructure, particularly where key connecting structures exist and where local amplification effects or geotechnical conditions may increase the severity of the impact. The observed pattern is consistent with a moderate but widespread contribution, given that earthquakes act as a regional hazard with broad coverage across the territory.

For fluvial flooding, the corresponding map shows a much stronger concentration along specific corridors associated with floodplains, proximity to river channels, and hydrological accumulation zones. In these cases, the AAL becomes highly localized, with segments that act as dominant points in the aggregated annual loss. The climate variability reported in the table can be interpreted spatially as a potential increase in the severity or frequency of flooding within these same critical corridors, amplifying the importance of certain sections within the road portfolio.

In the maps of earthquake-triggered landslides, losses are mainly concentrated in steep areas and in sectors where geotechnical susceptibility conditions the occurrence of shaking-induced failures. Unlike direct seismic risk, the spatial pattern here is more strongly controlled by geomorphology and by the hazard–terrain interaction, generating discrete zones of high loss that may coincide with segments of strategic connectivity within the road network. The expected annual Magnitude associated with this mechanism is lower than that of fluvial flooding or rainfall-triggered landslides, but its spatial distribution is particularly dependent on topography.

Finally, rainfall-triggered landslides present one of the most concentrated and sensitive spatial patterns in the analysis. Expected losses are grouped along specific road segments where steep slopes, susceptible soils, and hydrometeorological conditions capable of triggering recurrent instabilities coincide. This behavior is consistent with the high AAL values observed under maximum climate scenarios, where increases in precipitation extremes tend to be directly reflected in accumulated losses. In this case, the maps clearly identify that annual risk is dominated by a limited set of high-recurrence locations, which structure most of the contribution of rainfall-triggered landslides to the road sector portfolio.

5.2.2 Rail and Hydrocarbons Sectors

In this section, the rail and hydrocarbons sectors are presented together, solely for the convenience of representing them jointly in graphical form, since they are portfolios with a limited number of elements in Heredia.

5.2.2.1 Average Annual Loss (AAL)

Table 12 presents the AAL values by climate scenario for the rail and hydrocarbons sectors, this AAL values reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided. In order to limit the length of the document, only the baseline climate and the climates that produce the maximum and minimum AAL for hydrometeorological hazards are presented. Figure 41 and Figure 42 show the same information graphically.

Table 12. Average annual loss by hazard and climate scenario in the rail sector. Values in millions of Costa Rican colones (CRC).

Portfolio		Railway line		Pipeline	
<i>Exposed value</i>		\$ 986,648,800		\$ 3,743,233,900	
Hazard	Scenario	AAL	AAL (‰)	AAL	AAL (‰)
<i>Earthquake</i>		\$ 213,738	0.22	\$ 44,231	0.01
<i>Fluvial flood</i>	<i>Base</i>	\$ 219,831	0.22	\$ -	0.00
	<i>Min. 2035</i>	\$ 206,025	0.21	\$ -	0.00
	<i>Max. 2035</i>	\$ 258,076	0.26	\$ -	0.00
	<i>Min. 2050</i>	\$ 202,012	0.20	\$ -	0.00
	<i>Max. 2050</i>	\$ 284,509	0.29	\$ -	0.00
	<i>Min. 2100</i>	\$ 181,291	0.18	\$ -	0.00
	<i>Max. 2010</i>	\$ 264,416	0.27	\$ -	0.00
<i>Pluvial flood</i>	<i>Base</i>	\$ 986	0.00	\$ -	0.00
	<i>Min. 2035</i>	\$ 922	0.00	\$ -	0.00
	<i>Max. 2035</i>	\$ 1,165	0.00	\$ -	0.00
	<i>Min. 2050</i>	\$ 903	0.00	\$ -	0.00

Portfolio		Railway line		Pipeline	
<i>Exposed value</i>		\$ 986,648,800		\$ 3,743,233,900	
Hazard	Scenario	AAL	AAL (‰)	AAL	AAL (‰)
	<i>Max. 2050</i>	\$ 1,290	0.00	\$ -	0.00
	<i>Min. 2100</i>	\$ 808	0.00	\$ -	0.00
	<i>Max. 2010</i>	\$ 1,195	0.00	\$ -	0.00
<i>Earthquake-triggered landslide</i>		\$ 1,563	0.00	\$ 270,543	0.07
<i>Rainfall triggered landslide</i>	<i>Base</i>	\$ 6,675	0.01	\$ 1,067,669	0.29
	<i>Min. 2035</i>	\$ 6,463	0.01	\$ 1,016,956	0.27
	<i>Max. 2035</i>	\$ 7,301	0.01	\$ 1,155,026	0.31
	<i>Min. 2050</i>	\$ 4,041	0.00	\$ 940,431	0.25
	<i>Max. 2050</i>	\$ 7,226	0.01	\$ 1,203,021	0.32
	<i>Min. 2100</i>	\$ 3,979	0.00	\$ 660,302	0.18
	<i>Max. 2010</i>	\$ 7,377	0.01	\$ 1,210,332	0.32

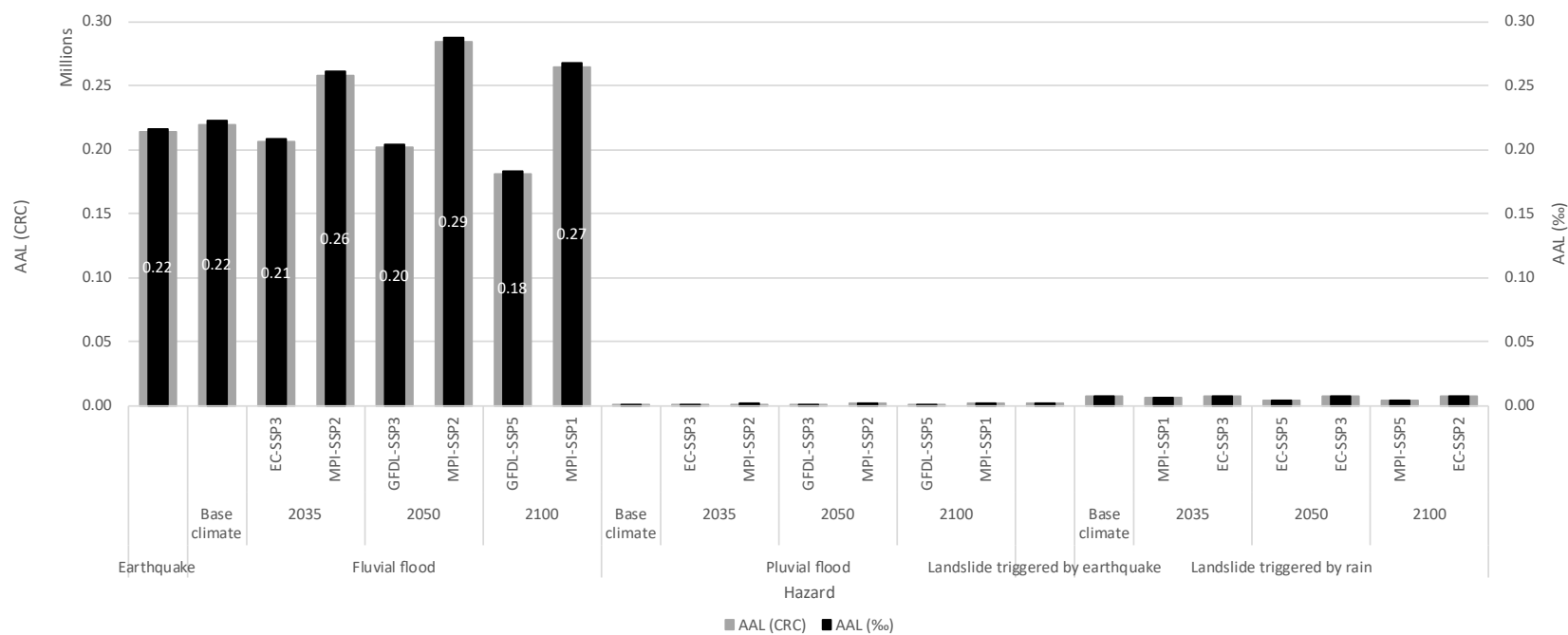


Figure 41. Average Annual Loss by Hazard for the railway sector

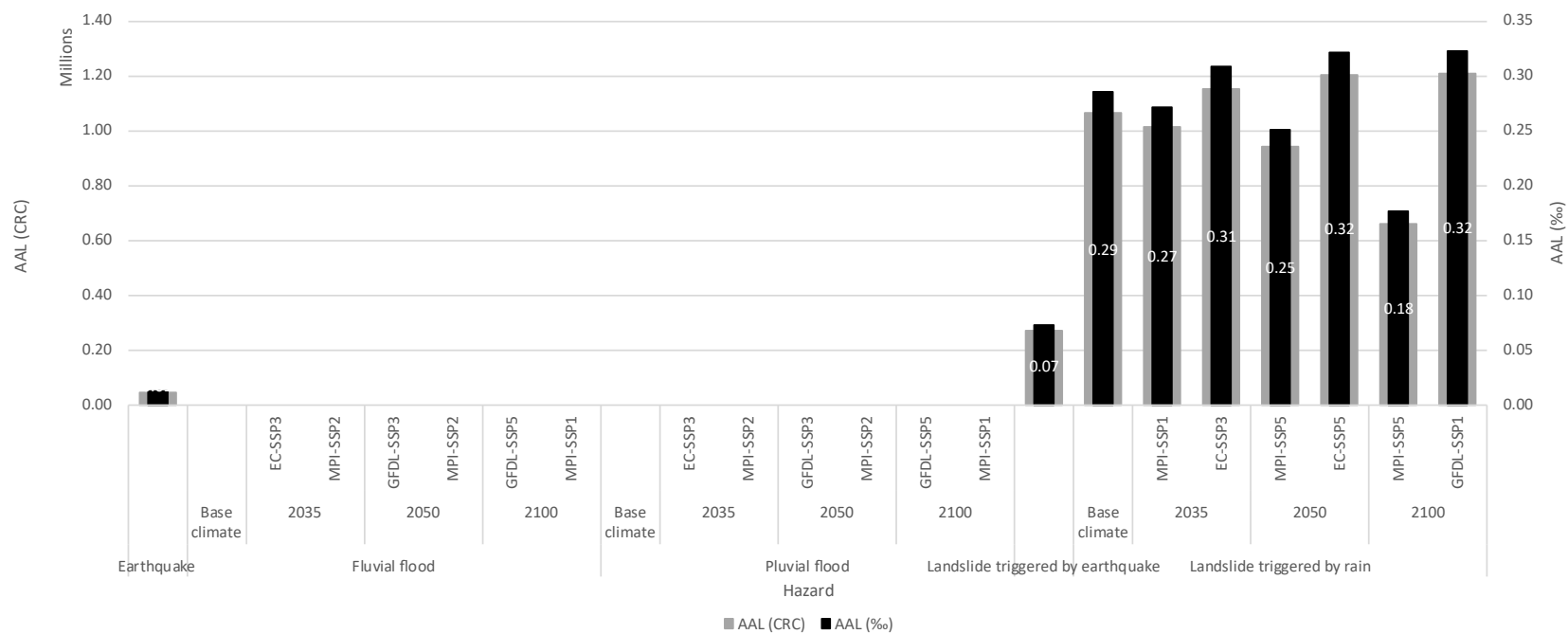


Figure 42. Average Annual Loss by hazard for the hydrocarbons sector

The AAL results for the rail sector show a relatively balanced distribution between seismic and hydrometeorological hazards, although with moderate annual magnitudes in absolute terms. The railway line presents AAL values on the order of CRC 0.21–0.26 million for fluvial flooding under the baseline scenario and future climates, with variability associated with the minimum and maximum projection limits. Direct seismic risk is comparable in magnitude, with an approximate AAL of CRC 0.214 million, while pluvial flooding is entirely marginal, with an almost negligible contribution to the annual total. Overall, for the rail component, fluvial and seismic hazards dominate the expected annual loss, with moderate climatic sensitivity reflected in the range of scenarios considered.

In contrast, the hydrocarbons sector, represented mainly by the pipeline (poliduct), exhibits a risk profile strongly conditioned by rainfall-triggered landslides. In this case, the AAL associated with this mechanism reaches values on the order of CRC 0.94–1.21 million, equivalent to relative losses of approximately 0.25–0.32‰ of the exposed value, clearly making it the main annual contributor within the portfolio. Direct seismic risk presents much lower annual losses (CRC 0.044 million), while earthquake-triggered landslides contribute additional relevant values (CRC 0.271 million). For fluvial and pluvial flooding, losses are zero.

5.2.2.2 Probable Maximum Loss (PML)

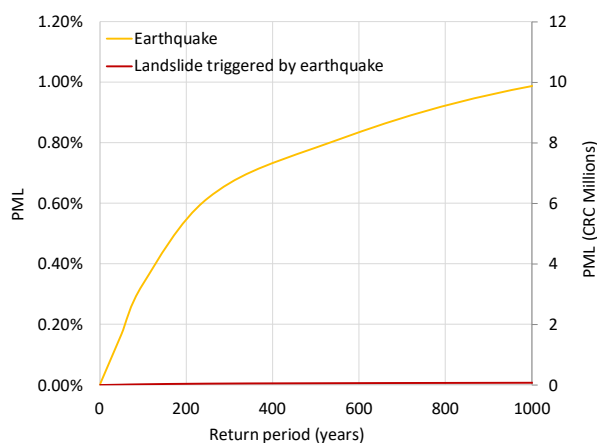
Figure 43 shows the PML curves for the rail sector, while Figure 44 presents the curves for the hydrocarbons sector. For the latter, fluvial and pluvial flooding are not included, as they do not generate losses in this portfolio.

The PML curves for the rail sector reveal differentiated behavior between regional hazards with broad spatial coverage, such as earthquakes, and localized hazards controlled by hydrometeorological processes. In the seismic case, the curves show a progressive increase in losses toward long return periods, representing the influence of low-frequency extreme events on the tail of the distribution. For earthquake-triggered landslides, the pattern similarly reflects losses concentrated in less frequent scenarios, although with smaller relative Magnitudes compared with the direct seismic component.

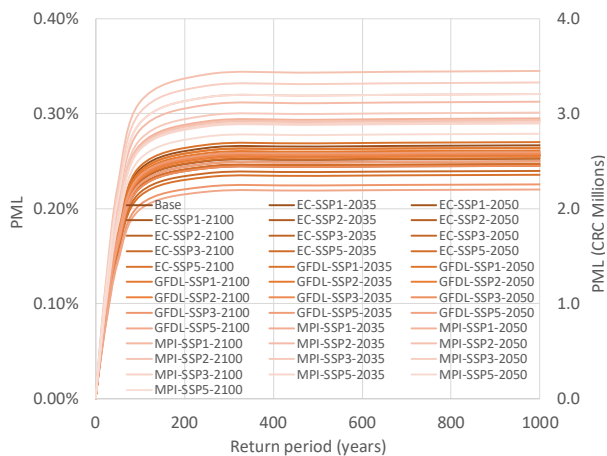
For the hydrocarbons subsector, the Probable Maximum Loss (PML) curves reflect an extreme risk profile dominated by slope instability mechanisms, with differentiated contributions between seismic and rainfall triggering. Direct seismic hazard presents a curve with gradual growth toward longer return periods. Earthquake-triggered landslides show a more localized pattern, but with relevant increases in the tail of the distribution, highlighting the capacity of severe seismic events to induce concentrated failures in critical segments.

However, the most dominant mechanism in terms of dispersion and extreme severity corresponds to rainfall-triggered landslides, where the set of curves associated with the 36 climate scenarios introduces substantial variability in the Magnitude of exceedance losses. Maximum future scenarios shift the distribution toward significantly higher loss levels at long return periods. Overall, the behavior of the curves indicates that the extreme risk of the hydrocarbons sector is primarily conditioned by mass movement processes under hydrometeorological forcing, with secondary but non-negligible contributions from seismic mechanisms.

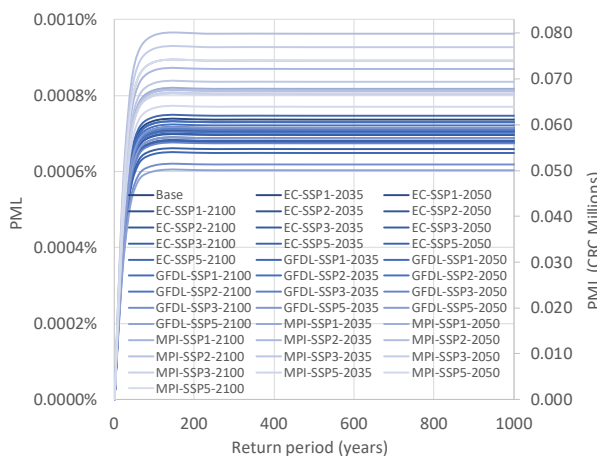
Earthquake and landslide triggered by earthquake



Fluvial flood



Pluvial flood



Landslide triggered by rain

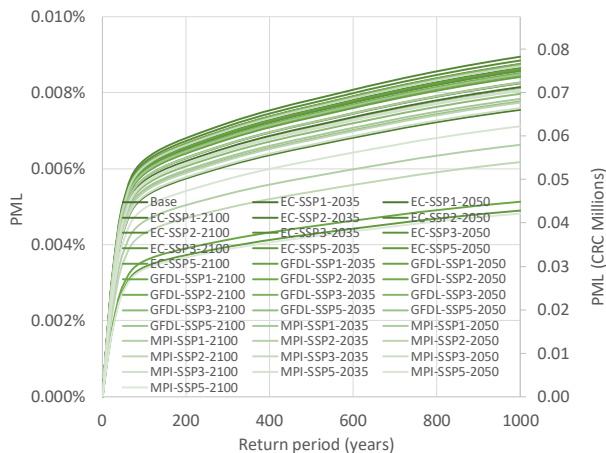
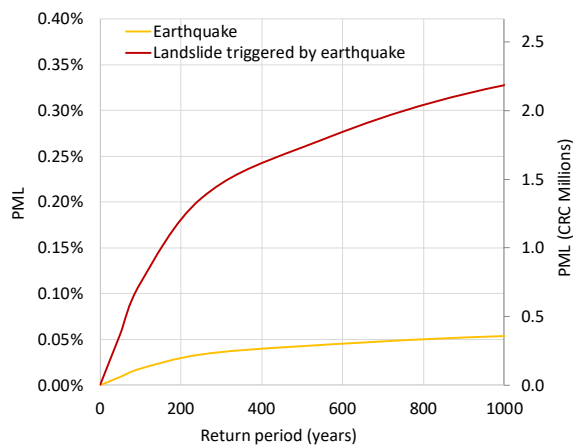


Figure 43. PML Curves for all considered hazards and all climate scenarios – Rail sector

Earthquake and landslide triggered by earthquake



Landslide triggered by rain

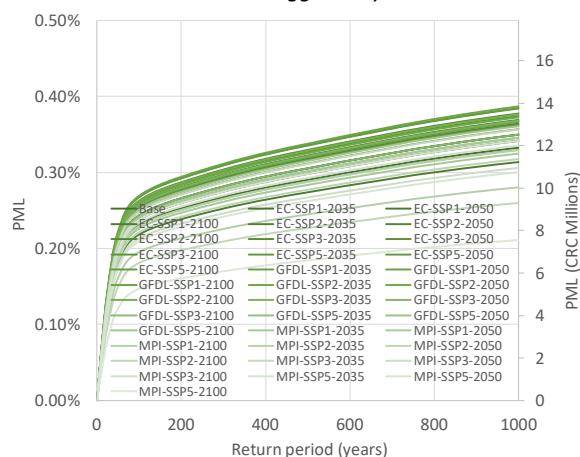


Figure 44. PML Curves for all considered hazards and all climate scenarios – Hydrocarbons sector

5.2.2.3 Losses by location

Figure 45 to Figure 49 present the AAL by element for the rail and hydrocarbons portfolios in Heredia, under the hazards considered.



Figure 45. Average Annual Loss due to earthquakes for the rail and hydrocarbons sectors in the canton of Heredia



Figure 46. Average Annual Loss due to fluvial flooding for the rail and hydrocarbons sectors in the canton of Heredia



Figure 47. Average Annual Loss due to pluvial flooding for the rail and hydrocarbons sectors in the canton of Heredia

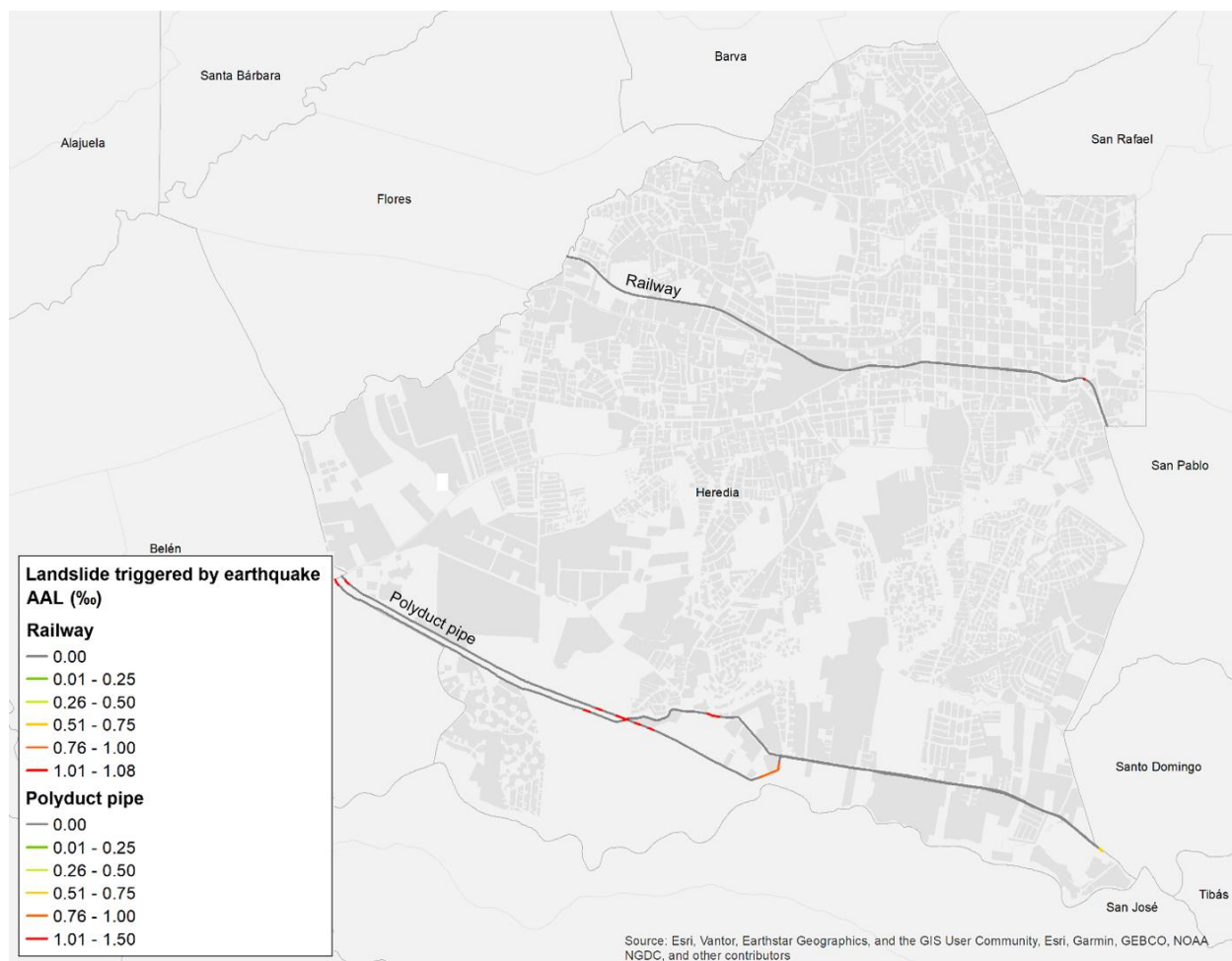


Figure 48. Average Annual Loss due to earthquake-triggered landslides for the rail and hydrocarbons sectors in the canton of Heredia

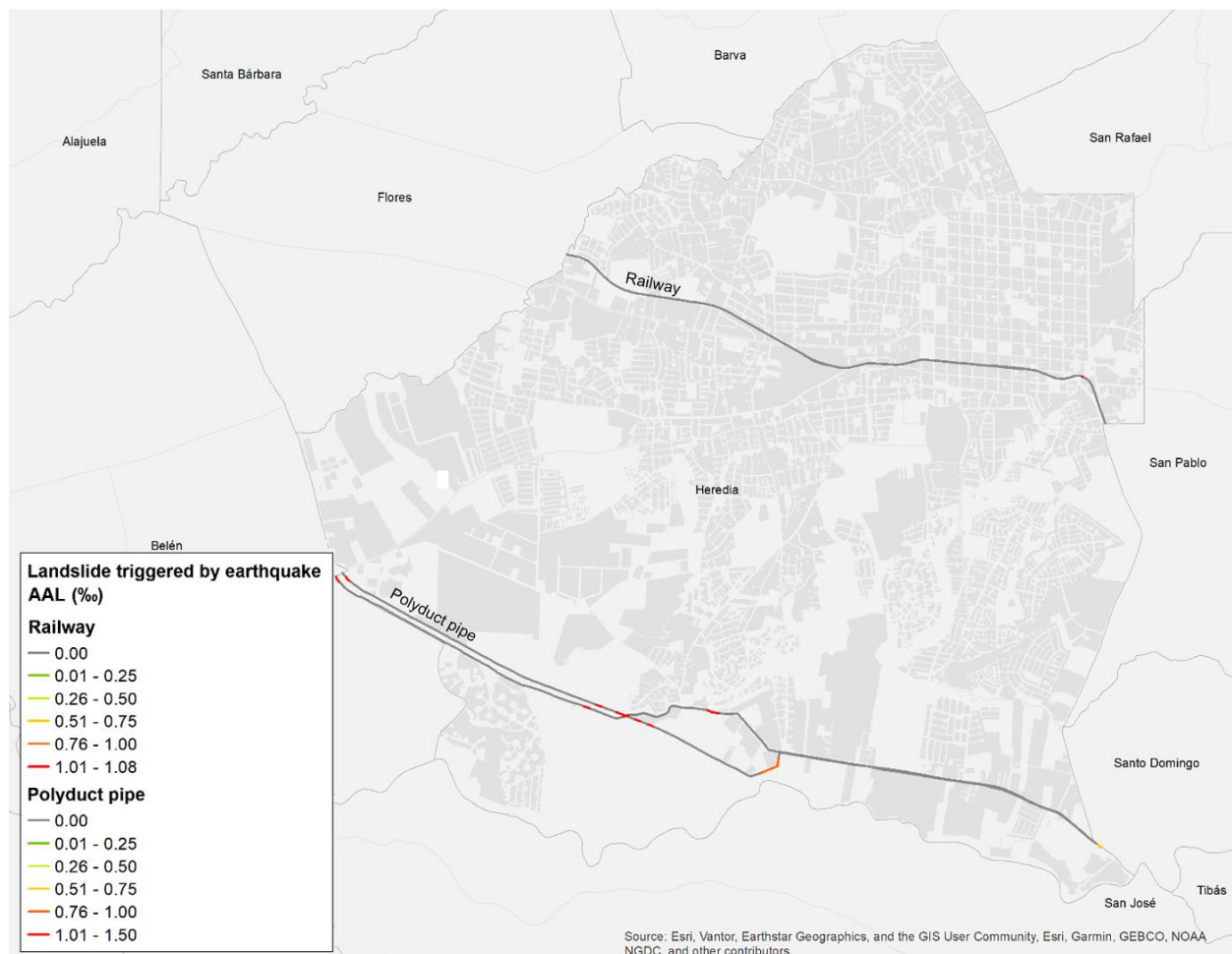


Figure 49. Average Annual Loss due to rainfall triggered landslides for the rail and hydrocarbons sectors in the canton of Heredia

The AAL maps by location for the rail and hydrocarbons sectors show a highly concentrated spatial distribution, where losses cluster in specific segments along the linear alignment of both systems. In the case of earthquakes, expected losses tend to be distributed relatively continuously along the infrastructure, reflecting the regional nature of seismic hazard, although with concentrations in sections where structural vulnerability or local conditions increase the expected damage. For earthquake-triggered landslides, the spatial pattern becomes more discrete and strongly dependent on topography, highlighting critical points associated with slope conditions and geotechnical susceptibility.

In the case of fluvial flooding, and especially rainfall-triggered landslides, the maps show more localized patterns dominated by specific corridors. Fluvial flooding concentrates losses in areas close to main river channels and overflow plains, although with no impact on the pipeline. In contrast, rainfall-triggered landslides generate the most significant clusters of annual loss within the hydrocarbons infrastructure, consistent with the high AAL values reported in the table and with the climate sensitivity observed in the PML curves. Since both sectors are represented jointly, the mapping illustrates how annual risk is structured by a limited subset of locations where linear exposure, critical slopes, and hydrometeorological forcing capable of triggering recurrent failures converge.

5.2.3 Electric Power Sector

For the electric power sector, results are presented for two subsectors: generation and transmission, and distribution. This facilitates the visualization of the sector's results, given that the geographical scales of these subsectors are different.

5.2.3.1 Average Annual Loss (AAL)

Table 13 presents the AAL values by climate scenario for generation and transmission, while Table 14 presents the AAL values for electricity distribution, this AAL values reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided. In order to limit the length of the document, only the baseline climate and the climates that produce the maximum and minimum AAL for hydrometeorological hazards are presented. Figure 50 shows the same information graphically and grouped for the entire electric power sector.

Table 13. Average annual loss by hazard and climate scenario in the electric power sector – Generation and transmission. Values in millions of Costa Rican colones (CRC).

Portfolio		Generation plants		Substations		Transmission towers		Transmission circuits	
Exposed value		\$28,867,904,000.00		\$649,373,800.00		\$2,141,500,000.00		\$90,268,400.00	
Hazard	Scenario	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)
Earthquake		\$51,687,082.30	1.79	\$3,307,840.40	5.09	\$857,672.70	0.40	\$6,235.60	0.07
Fluvial flood	Base	\$11,429,406.60	0.40	\$199,390.50	0.31	\$0.00	0.00	\$0.00	0.00
	Min. 2035	\$10,707,485.03	0.37	\$186,778.13	0.29	\$0.00	0.00	\$0.00	0.00
	Max. 2035	\$13,432,347.39	0.47	\$234,396.57	0.36	\$0.00	0.00	\$0.00	0.00
	Min. 2050	\$10,497,753.47	0.36	\$183,114.48	0.28	\$0.00	0.00	\$0.00	0.00
	Max. 2050	\$14,819,226.78	0.51	\$258,647.35	0.40	\$0.00	0.00	\$0.00	0.00
	Min. 2100	\$9,415,532.37	0.33	\$164,213.33	0.25	\$0.00	0.00	\$0.00	0.00
	Max. 2010	\$13,764,777.94	0.48	\$240,208.51	0.37	\$0.00	0.00	\$0.00	0.00
Pluvial flood	Base	\$100,926.30	0.00	\$15,260.30	0.02	\$0.00	0.00	\$0.00	0.00
	Min. 2035	\$94,372.74	0.00	\$14,269.37	0.02	\$0.00	0.00	\$0.00	0.00
	Max. 2035	\$119,238.37	0.00	\$18,029.11	0.03	\$0.00	0.00	\$0.00	0.00
	Min. 2050	\$92,473.42	0.00	\$13,982.19	0.02	\$0.00	0.00	\$0.00	0.00
	Max. 2050	\$132,030.57	0.00	\$19,963.32	0.03	\$0.00	0.00	\$0.00	0.00
	Min. 2100	\$82,705.77	0.00	\$12,505.30	0.02	\$0.00	0.00	\$0.00	0.00
	Max. 2010	\$122,296.19	0.00	\$18,491.46	0.03	\$0.00	0.00	\$0.00	0.00
Earthquake-triggered landslide		\$0.00	0.00	\$0.00	0.00	\$852,767.60	0.40	\$34,144.40	0.38
Rainfall triggered landslide	Base	\$0.00	0.00	\$0.00	0.00	\$3,267,481.80	1.53	\$119,422.40	1.32
	Min. 2035	\$0.00	0.00	\$0.00	0.00	\$3,116,467.76	1.46	\$113,899.76	1.26
	Max. 2035	\$0.00	0.00	\$0.00	0.00	\$3,518,296.46	1.64	\$128,414.89	1.42
	Min. 2050	\$0.00	0.00	\$0.00	0.00	\$2,900,756.02	1.35	\$106,214.76	1.18
	Max. 2050	\$0.00	0.00	\$0.00	0.00	\$3,670,592.72	1.71	\$134,006.83	1.48
	Min. 2100	\$0.00	0.00	\$0.00	0.00	\$2,066,882.41	0.97	\$75,995.50	0.84
	Max. 2010	\$0.00	0.00	\$0.00	0.00	\$3,732,046.41	1.74	\$137,522.95	1.52

Table 14. Average Annual Loss by hazard and climate scenario in the electric power sector – Distribution. Values in millions of Costa Rican colones (CRC).

Portfolio		Postes		Transformadores		Circuitos de distribución	
<i>Exposed value</i>		\$ 7,001,686,300		\$ 3,668,666,000		\$ 3,102,548,600	
Hazard	Scenario	AAL	AAL (%)	AAL	AAL (%)	AAL	AAL (%)
<i>Earthquake</i>		\$ 4,743,298	0.68	\$ 2,901,890	0.79	\$ 625,390	0.20
<i>Fluvial flood</i>	<i>Base</i>	\$ -	0.00	\$ 1,188,686	0.32	\$ -	0.00
	<i>Min. 2035</i>	\$ -	0.00	\$ 1,114,049	0.30	\$ -	0.00
	<i>Max. 2035</i>	\$ -	0.00	\$ 1,395,446	0.38	\$ -	0.00
	<i>Min. 2050</i>	\$ -	0.00	\$ 1,092,354	0.30	\$ -	0.00
	<i>Max. 2050</i>	\$ -	0.00	\$ 1,538,334	0.42	\$ -	0.00
	<i>Min. 2100</i>	\$ -	0.00	\$ 980,326	0.27	\$ -	0.00
	<i>Max. 2010</i>	\$ -	0.00	\$ 1,429,716	0.39	\$ -	0.00
<i>Pluvial flood</i>	<i>Base</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Min. 2035</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Max. 2035</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Min. 2050</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Max. 2050</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Min. 2100</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
	<i>Max. 2010</i>	\$ -	0.00	\$ -	0.00	\$ -	0.00
<i>Earthquake-triggered landslide</i>		\$ 213,529	0.03	\$ 92,629	0.03	\$ 104,421	0.03
<i>Rainfall triggered landslide</i>	<i>Base</i>	\$ 1,186,274	0.17	\$ 386,221	0.11	\$ 430,901	0.14
	<i>Min. 2035</i>	\$ 1,173,880	0.17	\$ 372,311	0.10	\$ 415,713	0.13
	<i>Max. 2035</i>	\$ 1,279,928	0.18	\$ 389,358	0.11	\$ 448,325	0.14
	<i>Min. 2050</i>	\$ 1,126,839	0.16	\$ 341,016	0.09	\$ 387,095	0.12
	<i>Max. 2050</i>	\$ 1,287,935	0.18	\$ 377,183	0.10	\$ 435,914	0.14
	<i>Min. 2100</i>	\$ 945,807	0.14	\$ 235,205	0.06	\$ 267,246	0.09
	<i>Max. 2010</i>	\$ 1,274,858	0.18	\$ 398,746	0.11	\$ 457,290	0.15

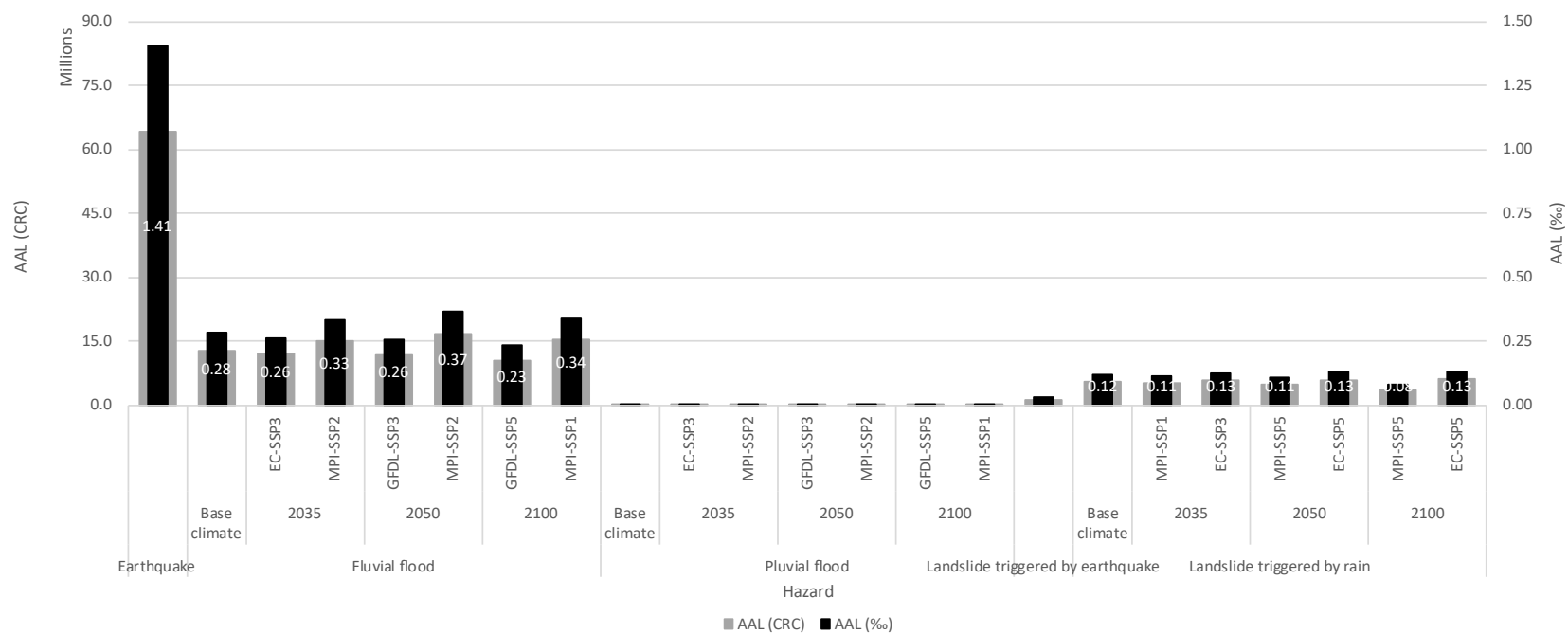


Figure 50. Average Annual Loss by hazard for the electric power sector

The Average Annual Loss (AAL) results for generation and transmission reveal important contrasts among the different asset types within the electric power system. In generation plants, earthquakes constitute the main annual contributor, with an AAL close to CRC 51.7 million ($\approx 1.79\%$), far exceeding the expected losses from fluvial flooding, which range between CRC 9.4 and 14.8 million depending on the climate scenario considered. Substations show a similar pattern, but with lower absolute losses and higher relative losses, with earthquakes standing out at CRC 3.3 million ($\approx 5.09\%$), while fluvial flooding contributes much smaller values. In contrast, the linear transmission infrastructure (towers and circuits) shows a significant contribution from slope processes, particularly rainfall-triggered landslides, with expected losses on the order of CRC 3.1–3.7 million for towers ($\approx 1.5\text{--}1.7\%$) and CRC 0.076–0.138 million for circuits ($\approx 0.8\text{--}1.5\%$).

In the distribution subsector, the expected annual profile is dominated by assets that are more spatially dispersed, with smaller Magnitudes but more balanced multi-hazard contributions. Poles present seismic annual losses close to CRC 4.74 million ($\approx 0.68\%$), while transformers reach CRC 2.9 million ($\approx 0.79\%$). For fluvial flooding, risk appears mainly concentrated in transformers, with values on the order of CRC 1.0–1.5 million, whereas poles and circuits show no relevant contribution. Additionally, rainfall-triggered landslides contribute consistent expected losses for the three asset types, with typical ranges between CRC 0.24 and 1.29 million, reflecting the sensitivity of the distribution system to local geomorphological conditions under alternative climate scenarios.

5.2.3.2 Probable Maximum Loss (PML)

Figure 51 shows the PML curves for the entire electric power sector under the hazards considered.

The PML curves for the electric power sector allow the characterization of how different hazards control the severity of losses in the extreme-event domain, while also distinguishing the effect of climate uncertainty in hydrometeorological processes. In the case of earthquakes, the curves show a progressive increase toward longer return periods, consistent with a regional hazard that simultaneously affects high-value concentrated assets, such as generation plants and substations. Earthquake-triggered landslides introduce an additional exceedance pattern associated with localized failures, particularly relevant for transmission infrastructure on slopes, where extreme damage depends on the interaction between ground shaking and terrain susceptibility.

For fluvial flooding and rainfall-triggered landslides, the spread of exceedance losses is especially visible in the transmission component. In fluvial flooding, climatic variability is manifested mainly in point assets (plants and substations), where maximum scenarios shift losses toward higher values at different exceedance levels. For rainfall-triggered landslides, the dispersion among curves is more pronounced in transmission towers and circuits, indicating that future climate extremes expand the plausible range of severe losses. Overall, the curves show that the loss tails of the electric power sector are structured by the combination of concentrated assets sensitive to earthquakes and linear assets exposed to slope processes conditioned by climate.

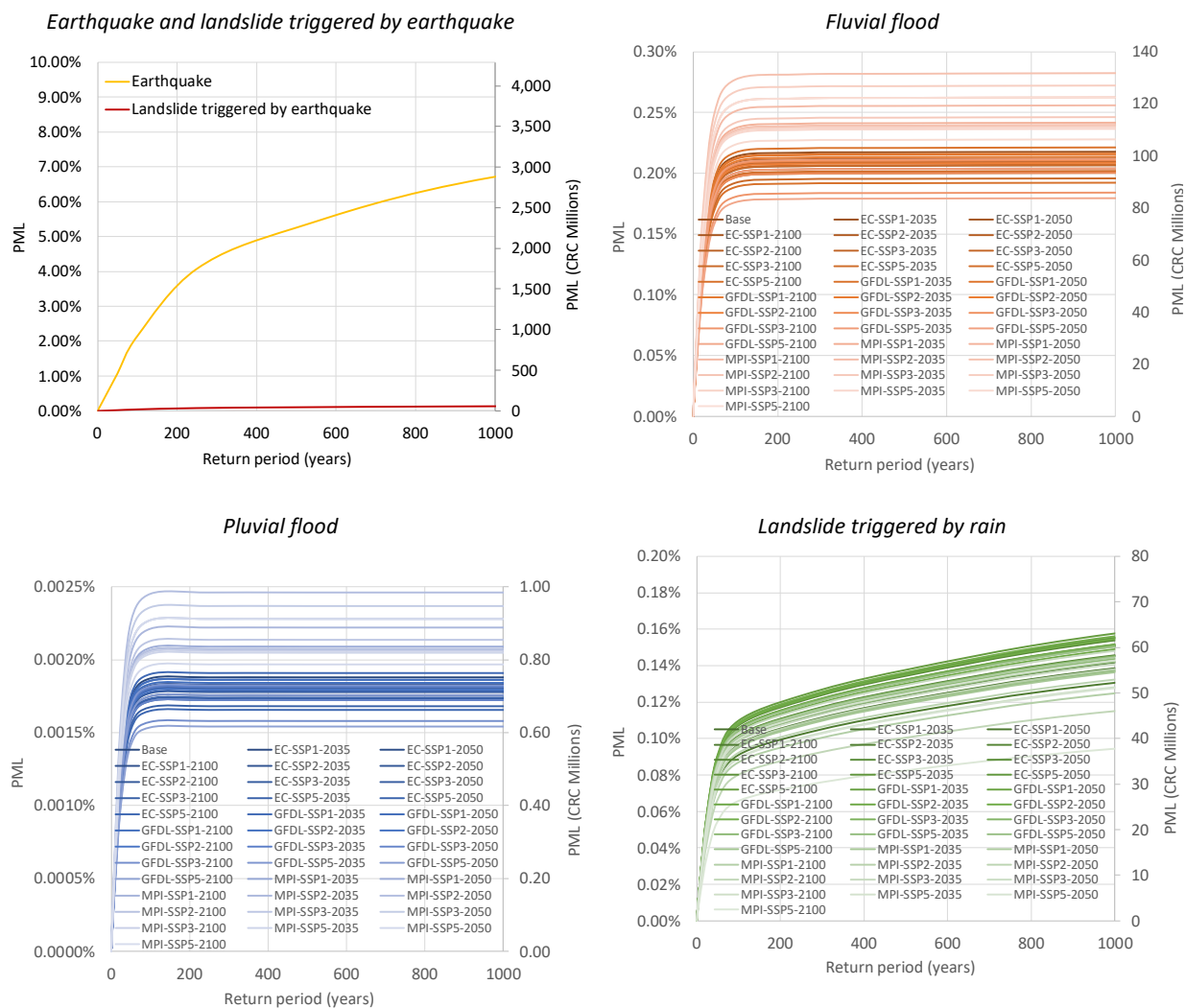


Figure 51. PML Curves for all considered hazards and all climate scenarios – Electric power sector

5.2.3.3 Losses by location

Figure 52 to Figure 56 present the AAL by element in the generation and transmission portfolio, while Figure 57 to Figure 60 present the results for the distribution portfolio.

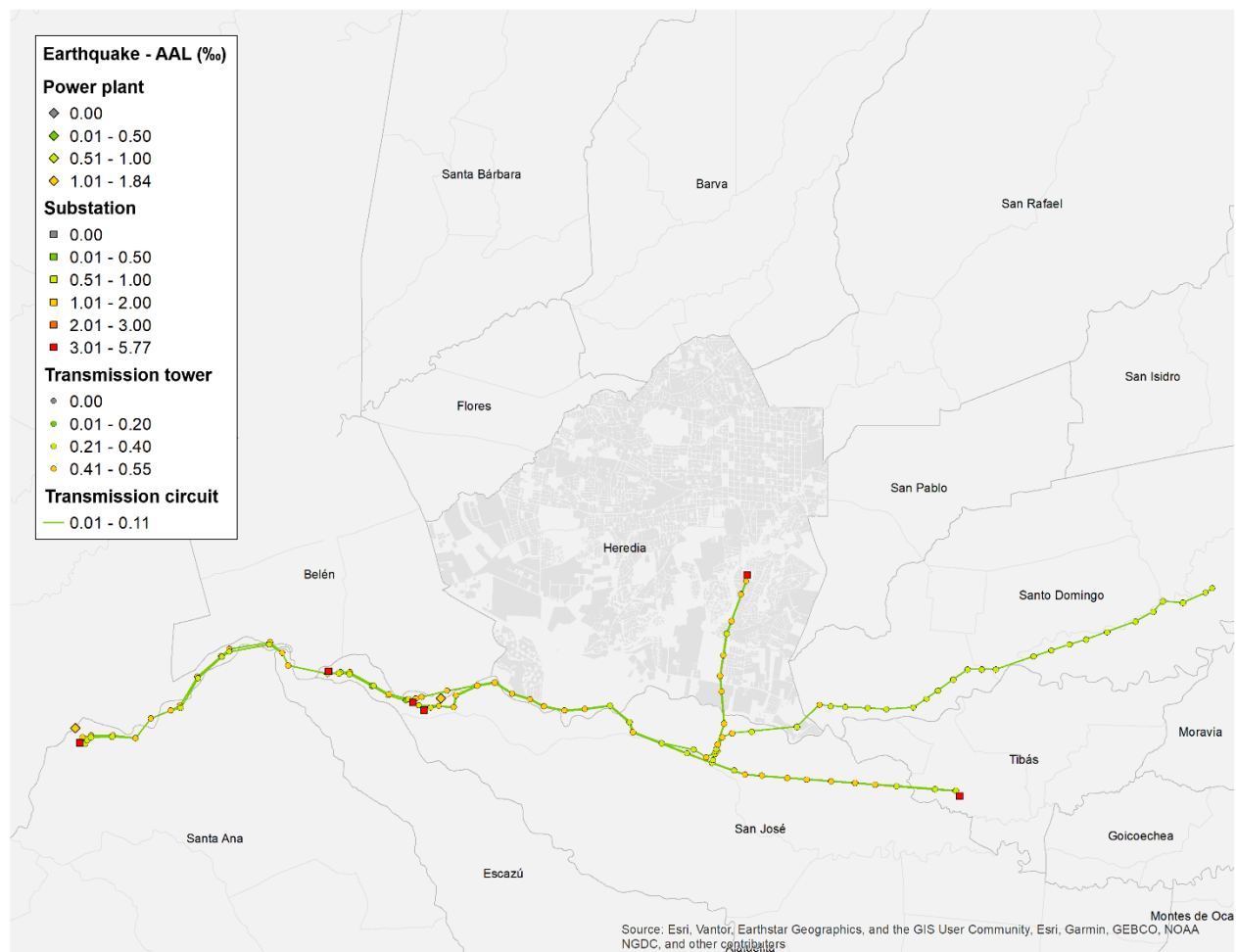


Figure 52. Average annual loss due to earthquakes for the electric power sector – Generation and transmission in the canton of Heredia

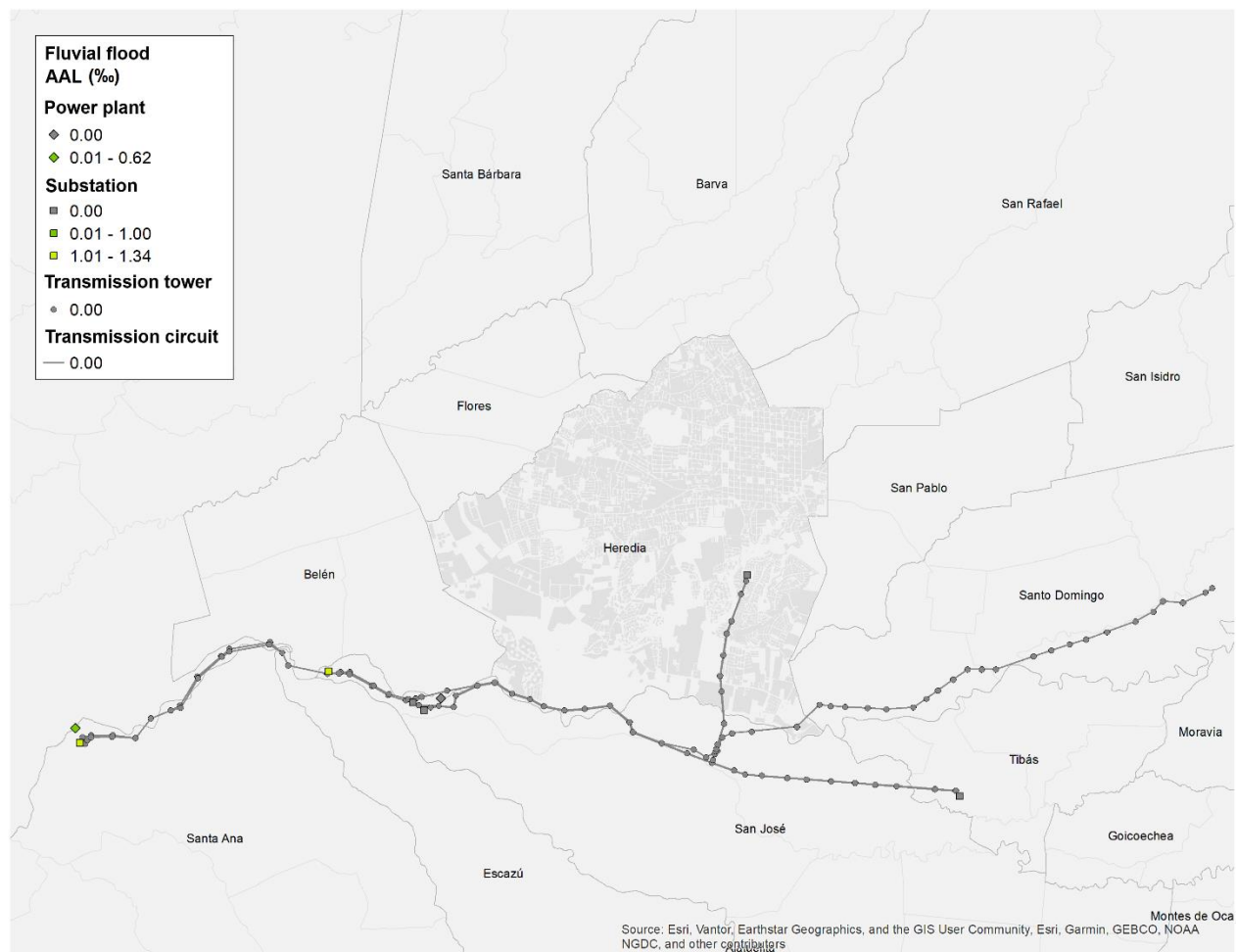


Figure 53. Average annual loss due to fluvial flooding for the electric power sector – Generation and transmission in the canton of Heredia

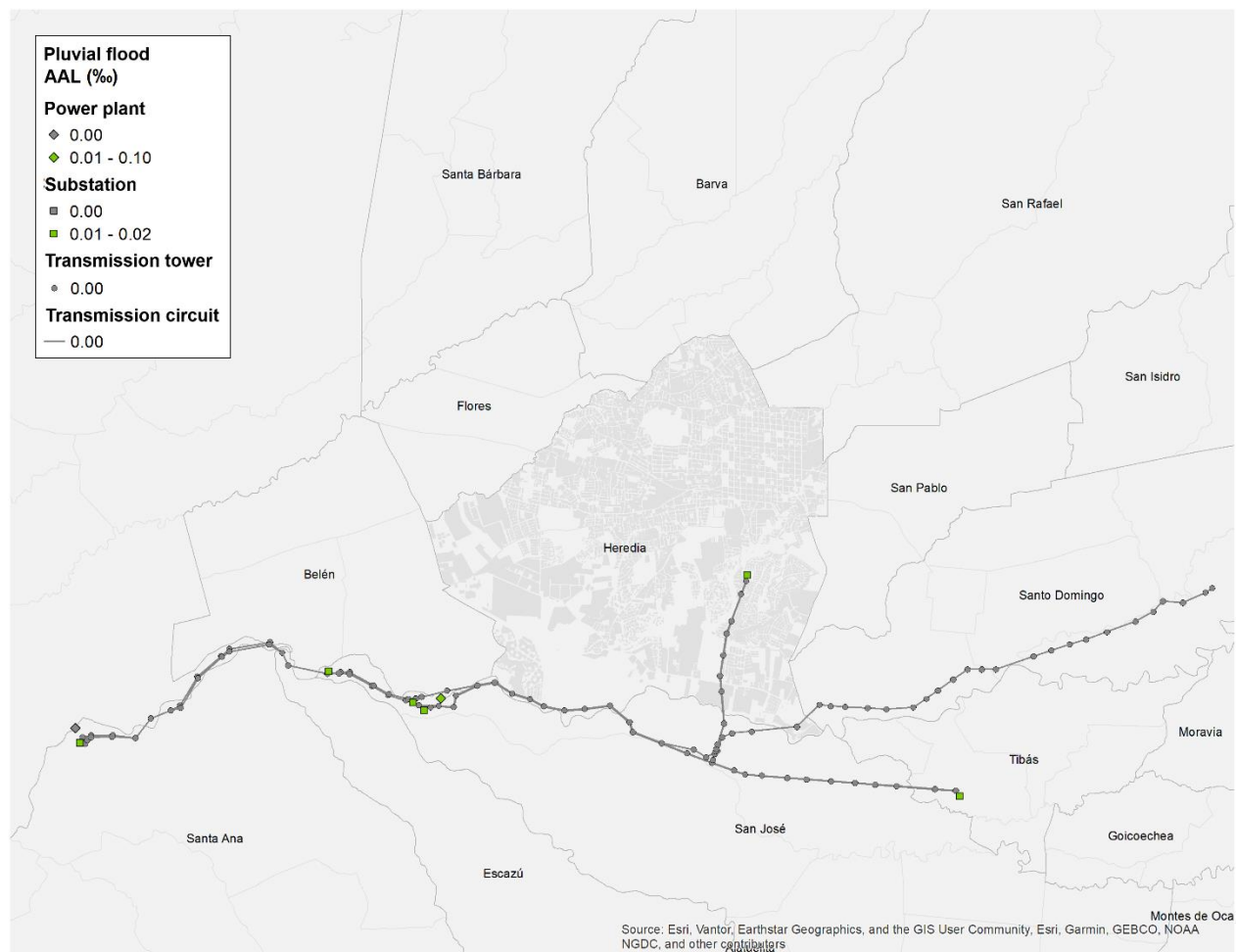


Figure 54. Average annual loss due to pluvial flooding for the electric power sector – Generation and transmission in the canton of Heredia

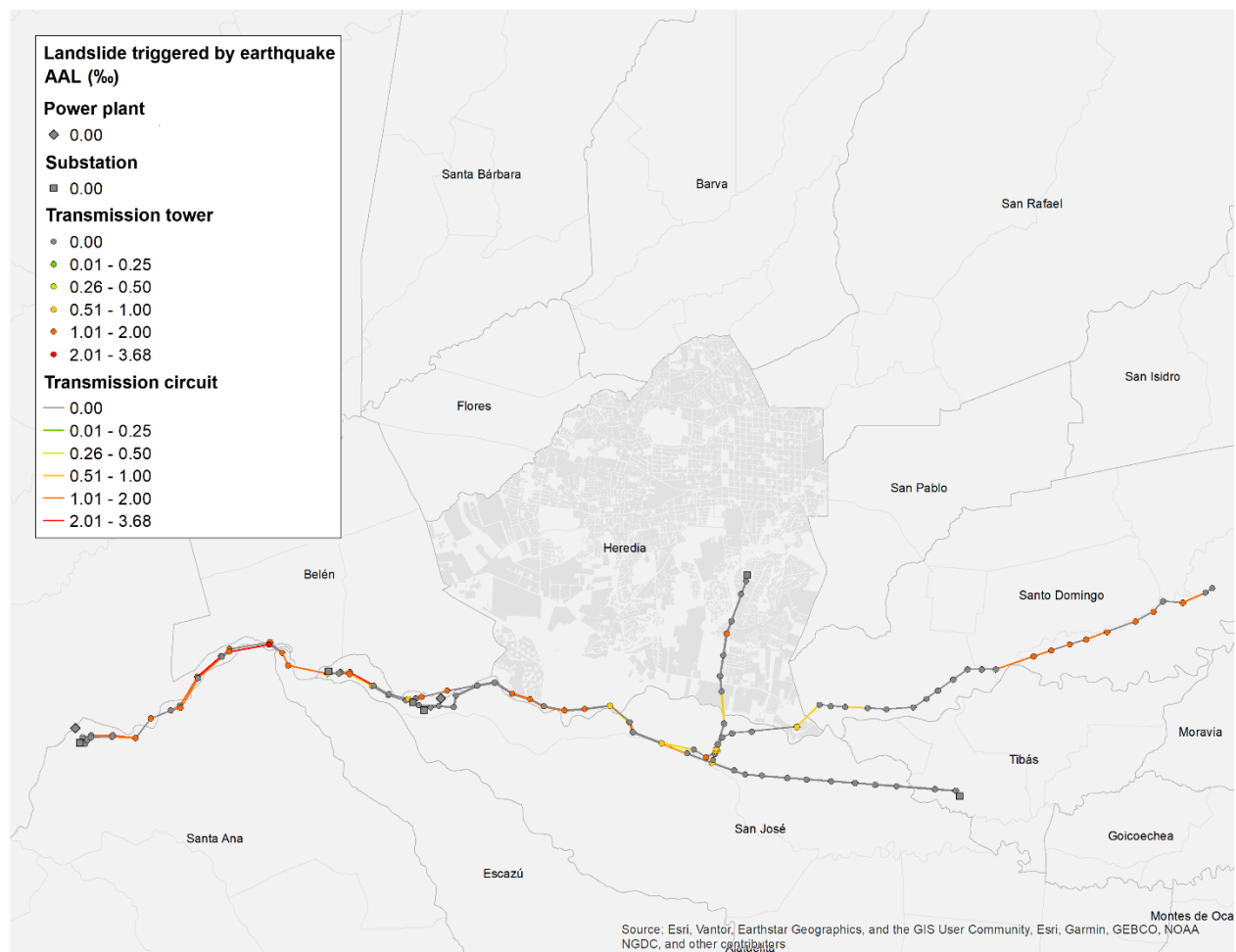


Figure 55. Average annual loss due to earthquake-triggered landslides for the electric power sector – Generation and transmission in the canton of Heredia

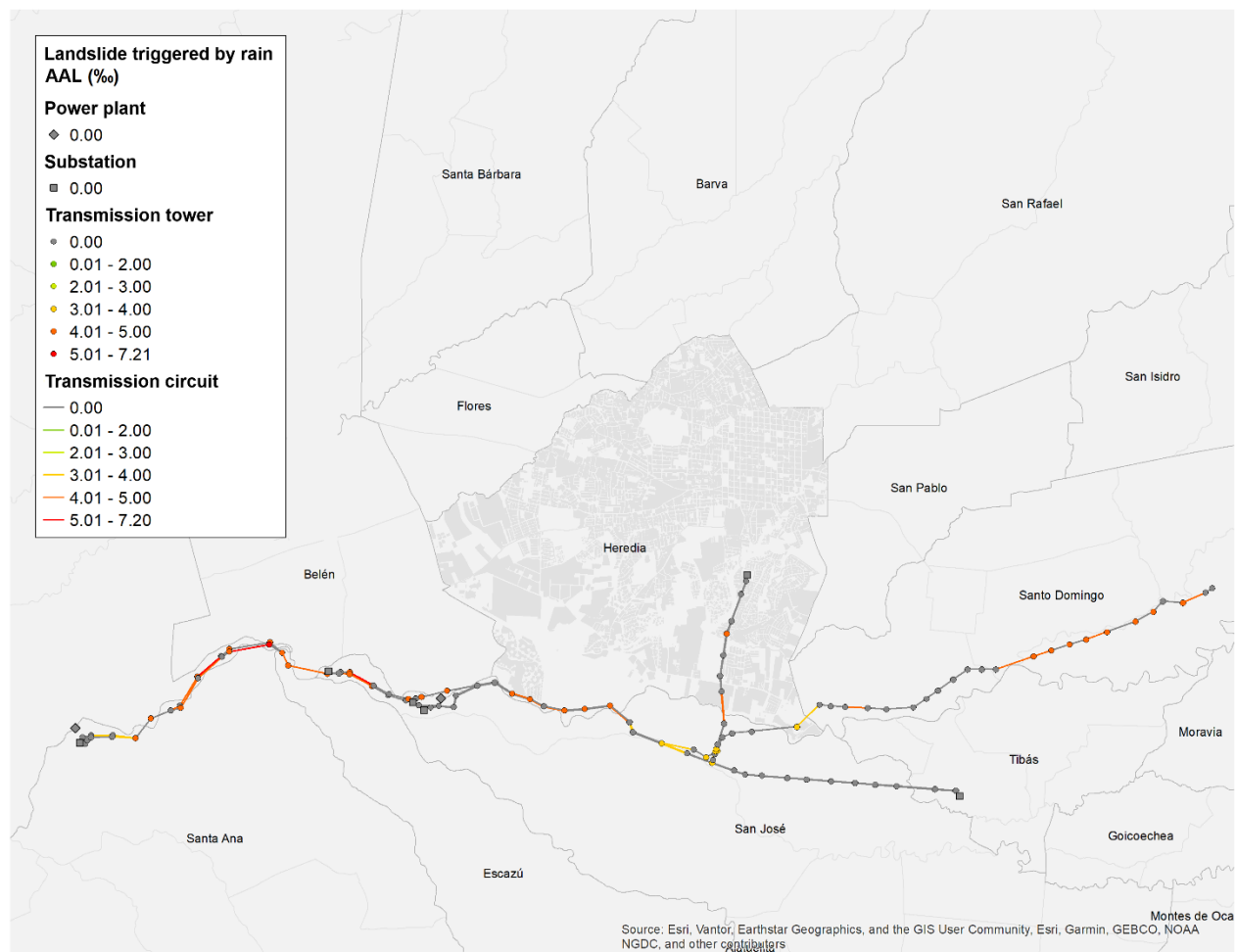


Figure 56. Average annual loss due to rainfall triggered landslides for the electric power sector – Generation and transmission in the canton of Heredia

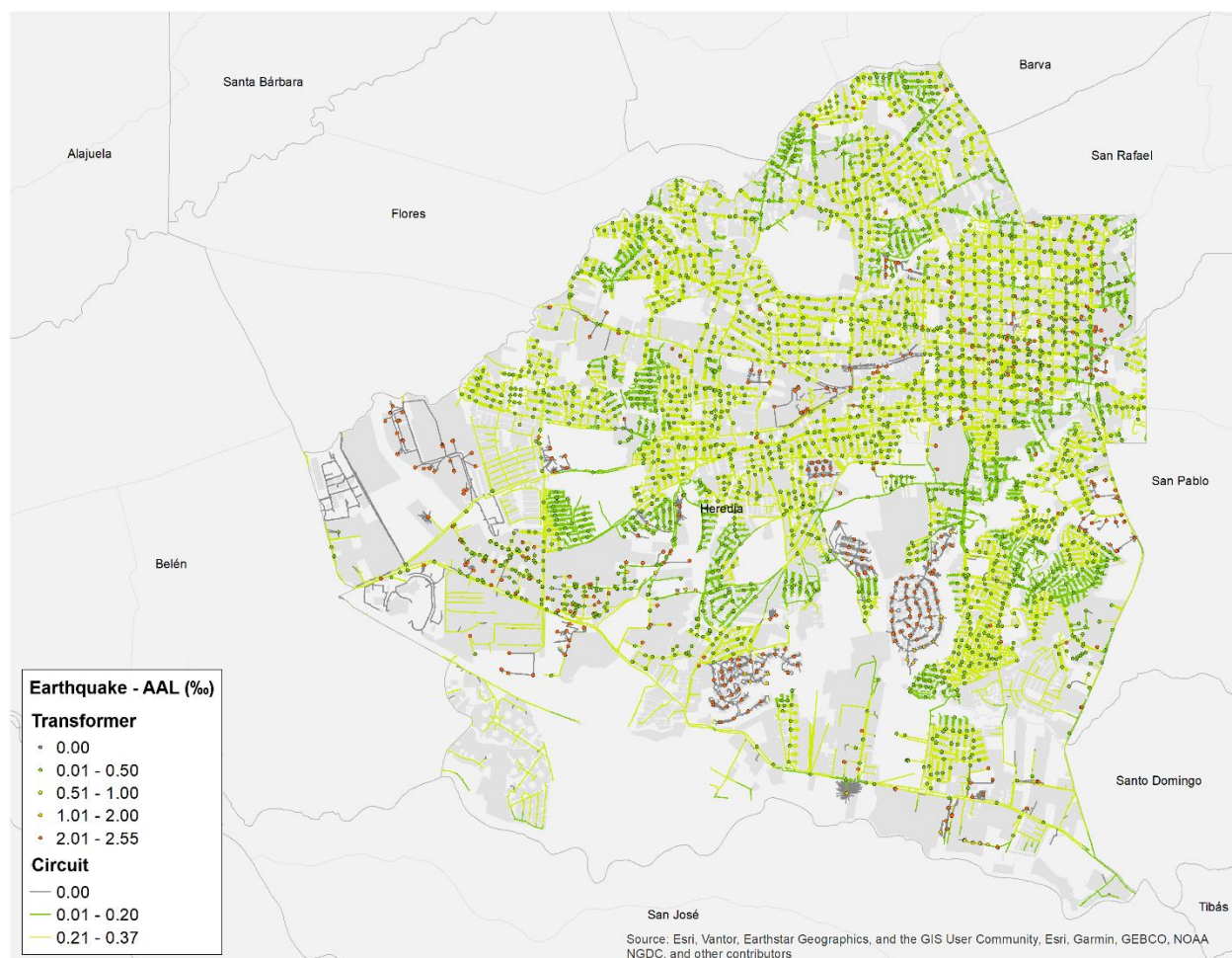


Figure 57. Average Annual Loss due to earthquakes for the electric power sector – Distribution – in the canton of Heredia

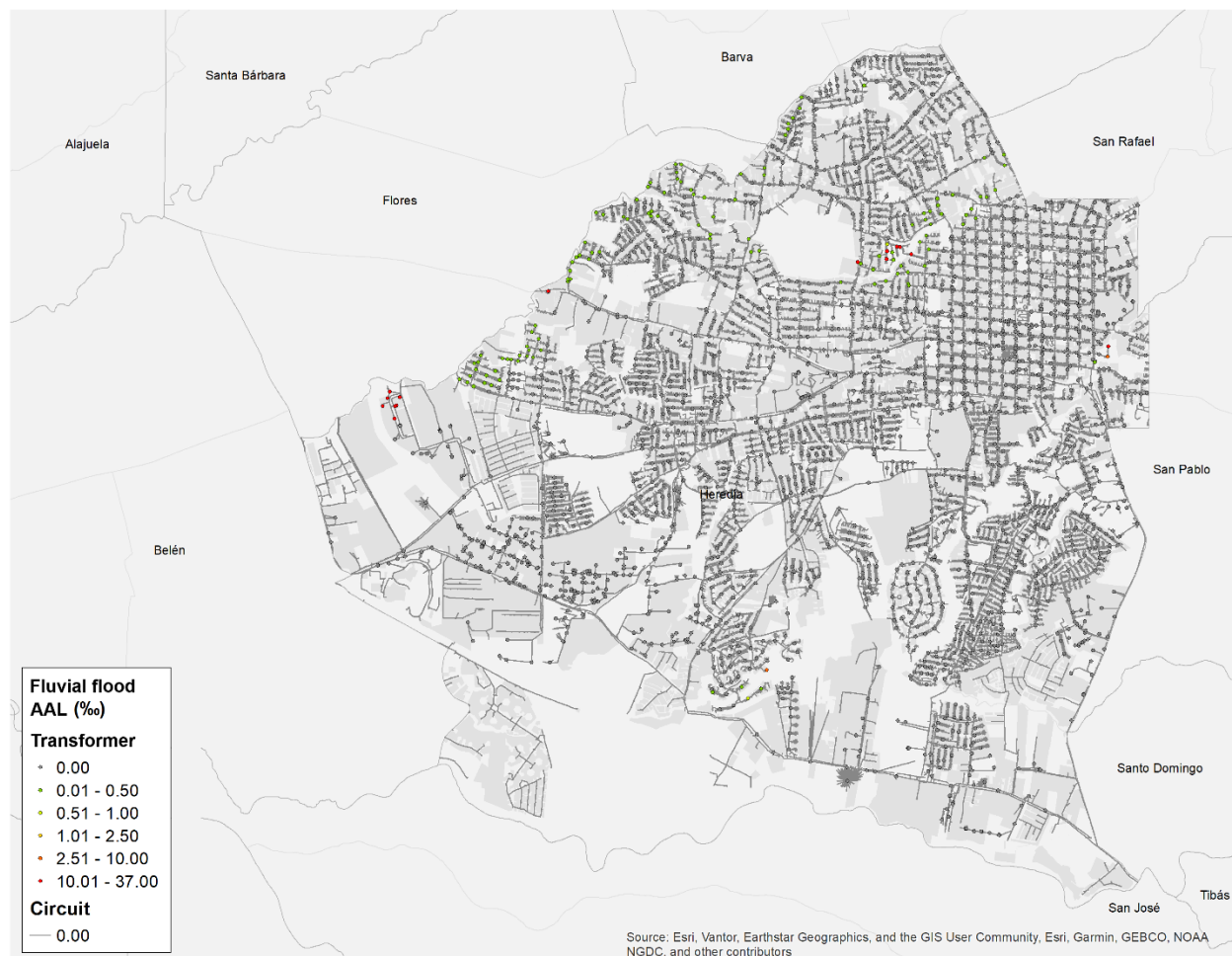


Figure 58. Average Annual Loss due to fluvial flooding for the electric power sector – Distribution – in the canton of Heredia

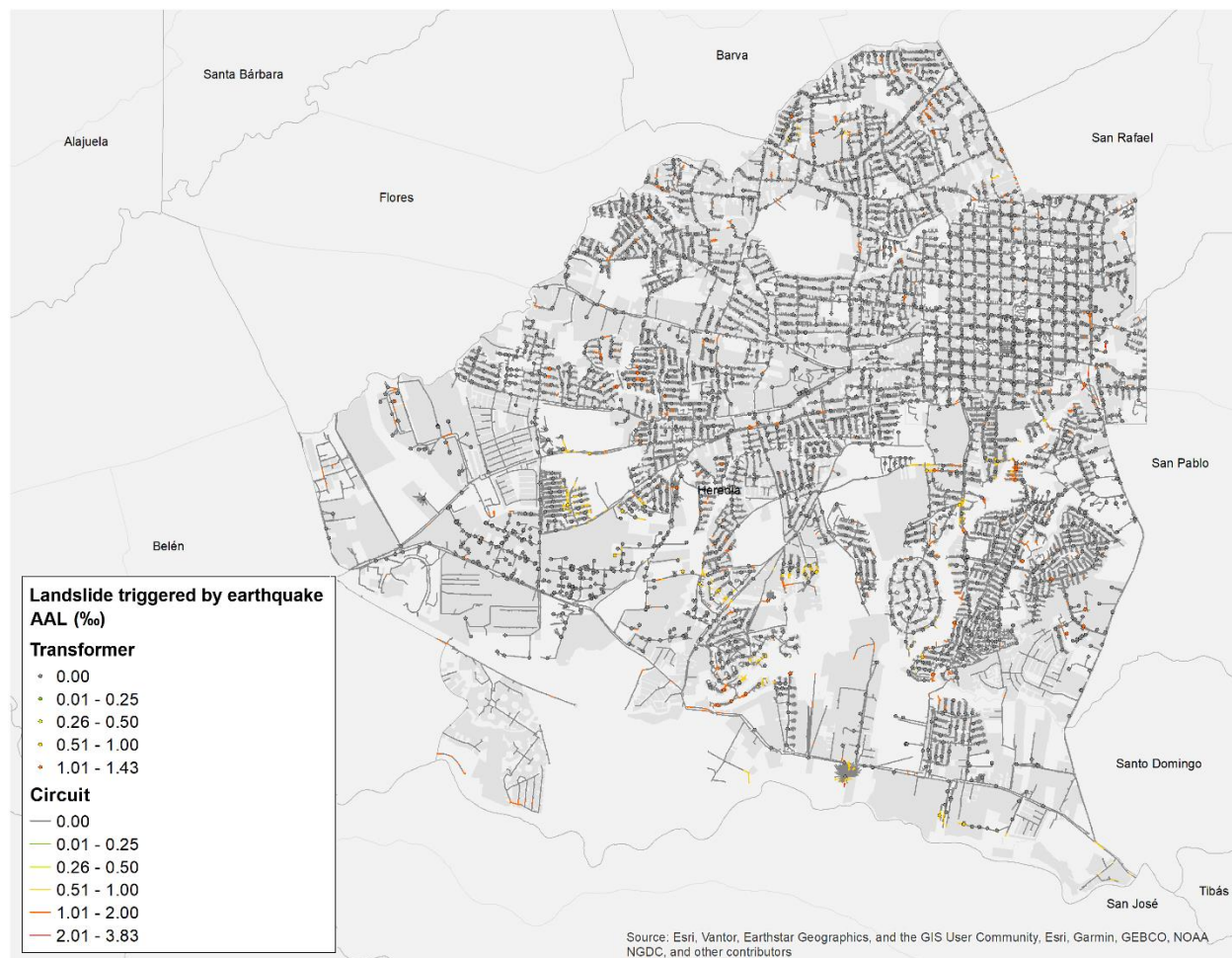


Figure 59. Average Annual Loss due to earthquake-triggered landslides for the electric power sector – Distribution – in the canton of Heredia

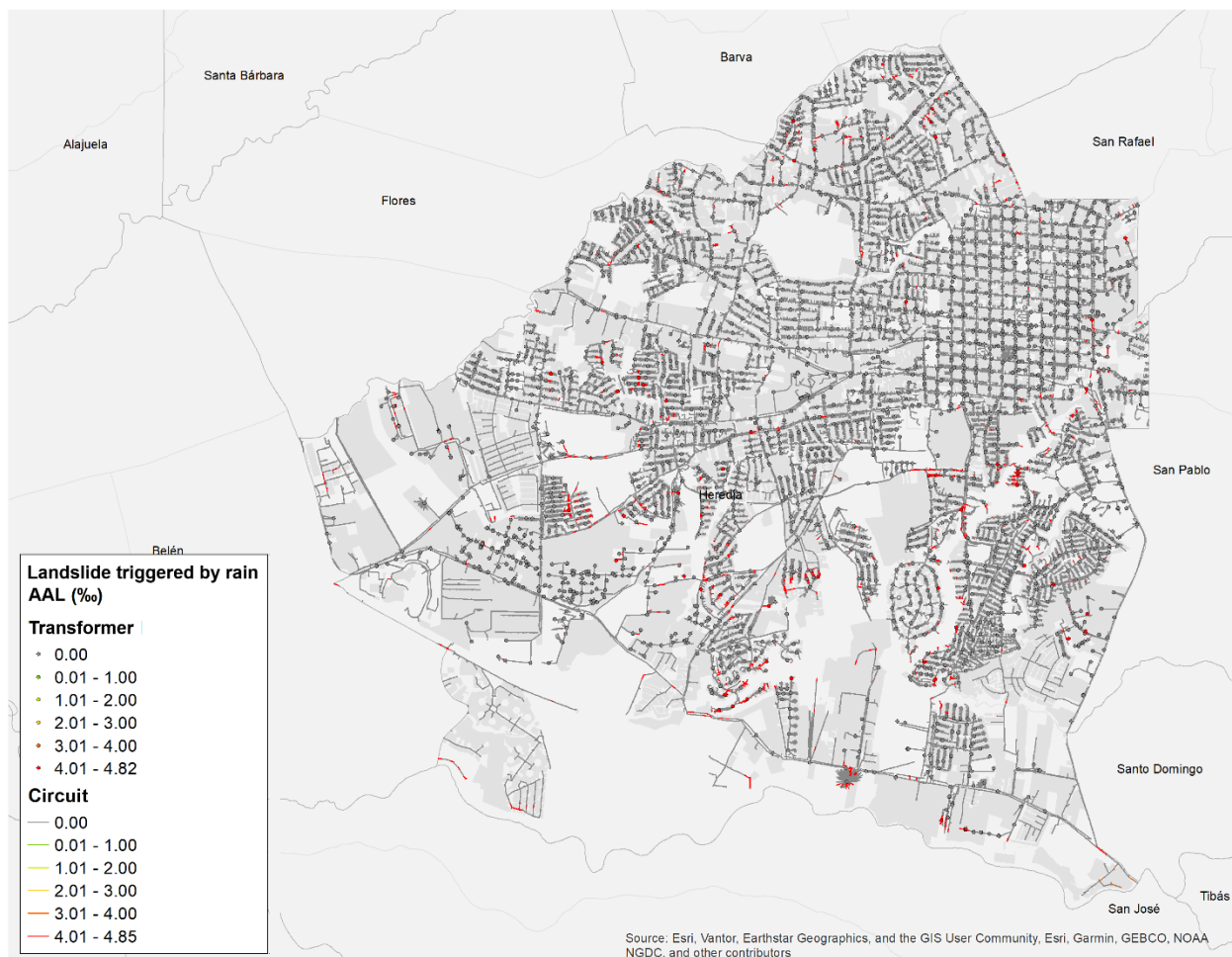


Figure 60. Average Annual Loss due to rainfall-triggered landslides for the electric power sector – Distribution – in the canton of Heredia

The AAL maps by location for generation and transmission show that seismic risk is mainly organized around strategic nodes of the system, such as plants and substations, where higher expected values concentrate due to the accumulation of exposed value. For fluvial flooding, the mapping reveals an even stronger concentration in specific areas of the canton associated with proximity to river channels and low-lying zones, predominantly affecting point infrastructure. In contrast, the maps of rainfall-triggered landslides display a more linear and segmented pattern, highlighting transmission segments where the slope–precipitation interaction produces dominant annual contributions, consistent with the high AAL values reported for towers and circuits.

In the case of distribution, the maps reflect a much broader territorial dispersion, as poles, transformers, and circuits are widely distributed throughout the urban and peri-urban fabric. Seismic risk appears relatively widespread, with moderate but continuous expected losses. For fluvial flooding, loss concentrations are limited mainly to transformers in specific locations, while landslides, both earthquake-triggered and rainfall-triggered, generate clusters in hillside sectors that simultaneously affect multiple elements of the secondary network.

Overall, the spatial representation of the electric power sector highlights the coexistence of highly nodal losses in generation and transmission and more diffuse but territorially extensive losses in distribution, with distinct patterns depending on the hazard type.

5.2.4 Communications Sector

5.2.4.1 Average Annual Loss (AAL)

Table 15 presents the AAL values for the communications sector, this AAL values reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided. In order to limit the length of the document, only the baseline climate and the climates that produce the maximum and minimum AAL for hydrometeorological hazards are presented. Figure 61 shows the same information graphically.

Table 15. Average annual loss by hazard and climate scenario in the communications sector. Values in millions of Costa Rican colones (CRC).

Portfolio		Antennas	
Exposed value		\$ 2,230,418,300	
Hazard	Scenario	AAL	AAL (‰)
Earthquake		\$ 1,454,168	0.65
Fluvial flood	Base	\$ 191,002	0.09
	Min. 2035	\$ 179,004	0.08
	Max. 2035	\$ 224,241	0.10
	Min. 2050	\$ 175,517	0.08
	Max. 2050	\$ 247,215	0.11
	Min. 2100	\$ 157,510	0.07
	Max. 2100	\$ 229,751	0.10
Pluvial flood	Base	\$ -	0.00
	Min. 2035	\$ -	0.00
	Max. 2035	\$ -	0.00
	Min. 2050	\$ -	0.00
	Max. 2050	\$ -	0.00
	Min. 2100	\$ -	0.00
	Max. 2100	\$ -	0.00
Desliz. detonado por Earthquake		\$ -	0.00
Desliz. detonado por lluvia	Base	\$ 558,029	0.25
	Min. 2035	\$ 552,377	0.25
	Max. 2035	\$ 670,273	0.30
	Min. 2050	\$ 534,201	0.24
	Max. 2050	\$ 670,626	0.30
	Min. 2100	\$ 534,630	0.24
	Max. 2100	\$ 885,049	0.40

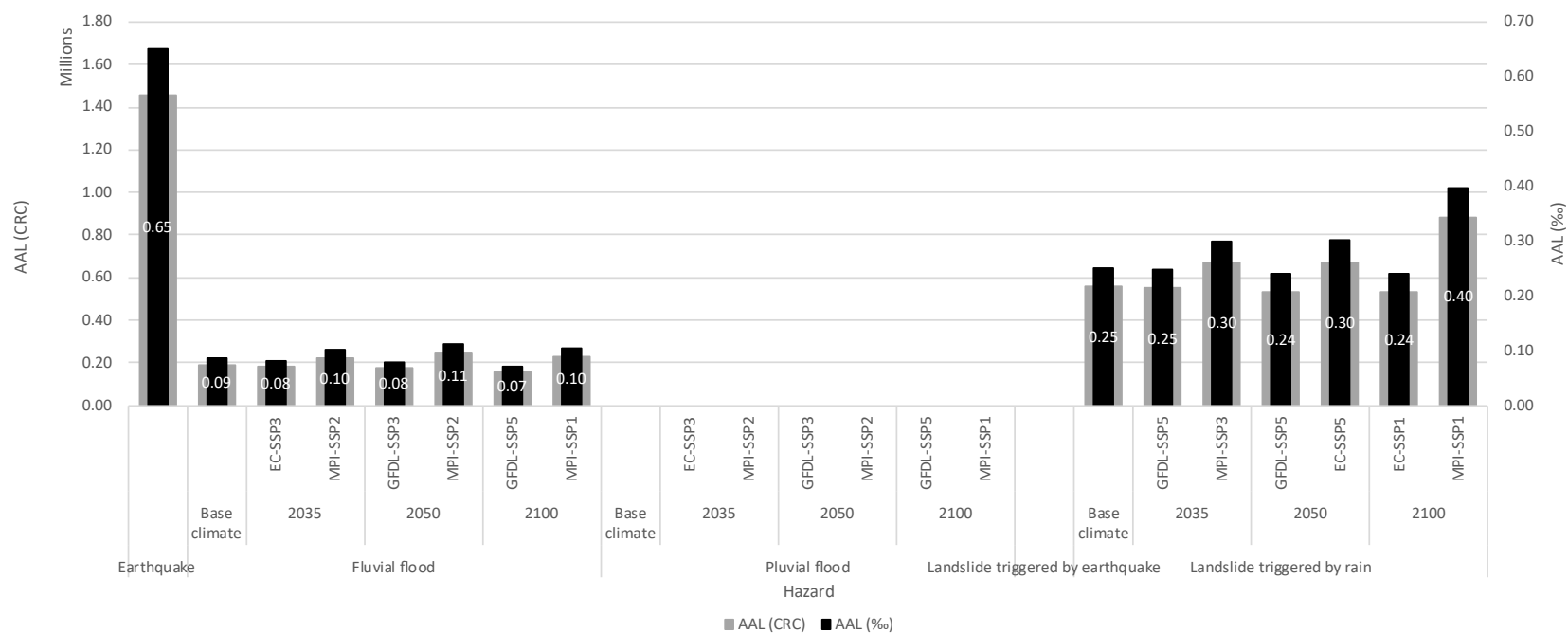


Figure 61. Average Annual Loss by hazard for the communications sector

The results for the antenna portfolio show a profile of relatively low annual losses in absolute Magnitude, consistent with the size of the exposed value of the subsector ($\approx$ CRC 2.23 billion). Earthquakes constitute the main individual contributor, with an AAL close to CRC 1.45 million, equivalent to a relative loss of approximately 0.65%, positioning it as the dominant mechanism among the regional hazards included in the analysis. In comparison, fluvial flooding presents much smaller expected losses, on the order of CRC 0.19 million under the baseline scenario, with moderate variations across minimum and maximum climate scenarios.

On the other hand, rainfall-triggered landslides represent a significant hydrometeorological component in relative terms, with a baseline AAL of CRC 0.56 million ($\approx$ 0.25%) and a range increasing up to CRC 0.89 million ($\approx$ 0.40%) under the climate scenario producing the highest losses. This behavior shows that, although absolute losses remain moderate, climate sensitivity in mass movement processes can generate appreciable increases in the expected annual risk of the subsector. In contrast, both pluvial flooding and earthquake-triggered landslides are null for this portfolio, indicating the absence of modeled damage or relevant exposure for these mechanisms.

Although the loss values are low, the risk to this sector should not be considered negligible, since, as mentioned in Section 2.4, this analysis is limited to the physical component of the assets (antennas) and does not include the service provided, which could likely greatly exceed the direct physical value of the affected elements.

5.2.4.2 Probable Maximum Loss (PML)

Figure 62 shows the PML curves for the telecommunications sector under the hazards considered. Pluvial flooding is not included, as the risk from this hazard is null.

The PML curves for the communications sector reflect a limited set of dominant hazards, with the explicit exclusion of pluvial flooding due to its null risk. In the seismic case, the curve shows a progressive increase in exceedance losses toward longer return periods, capturing the role of extreme regional events that simultaneously affect point assets of high functional importance. For earthquake-triggered landslides, the associated curve represents a secondary contribution, consistent with the absence of expected annual losses for this mechanism, suggesting that no relevant shaking-induced impact scenarios were identified at the locations considered.

For fluvial flooding, the dispersion among climate-based PML curves is moderate and remains within a bounded range, consistent with the low expected annual losses. In the case of rainfall-triggered landslides, the separation among scenarios is more pronounced, with maximum curves shifting toward higher losses at low and medium exceedance levels.

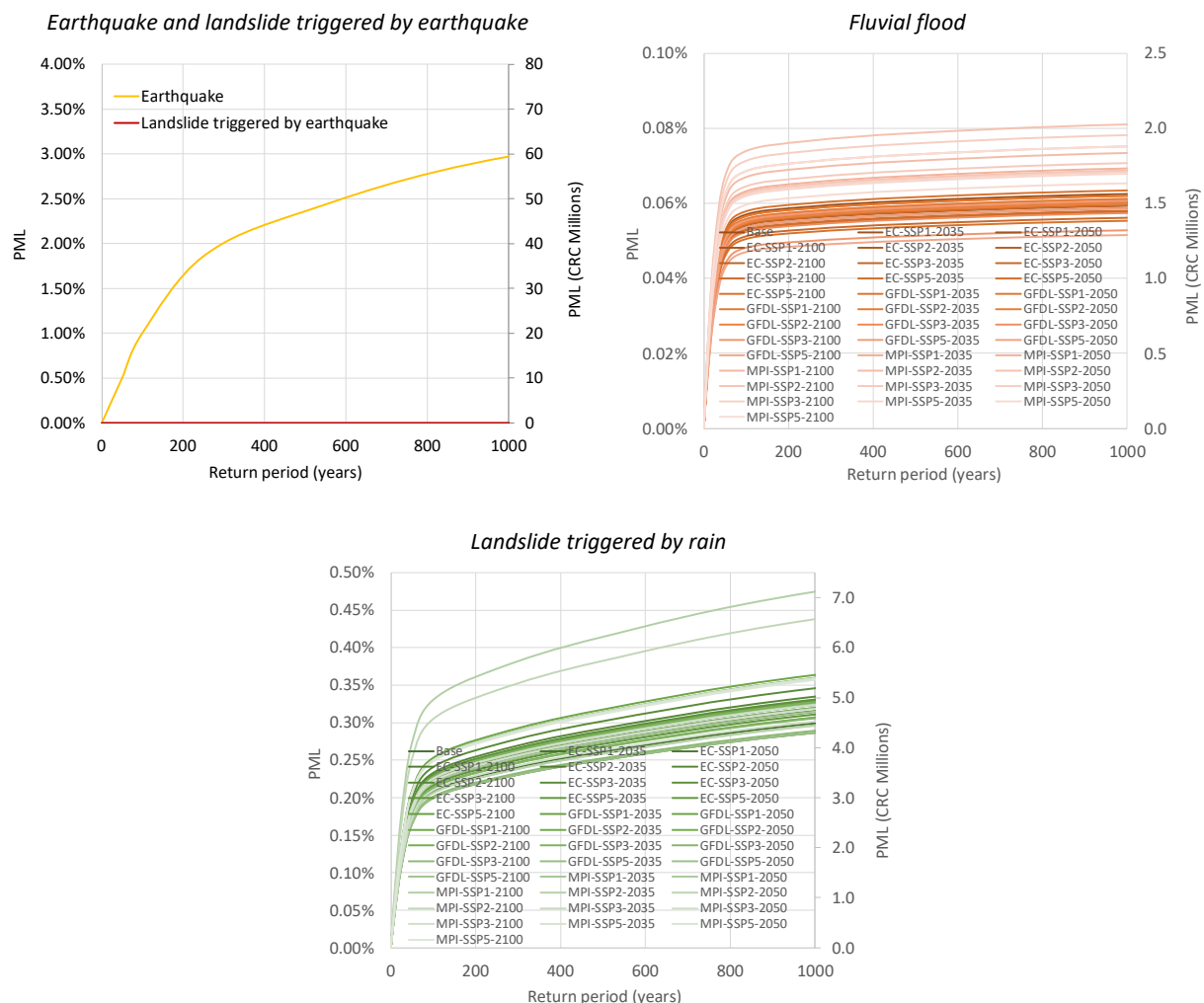


Figure 62. PML curves for all considered hazards and all climate scenarios – Communications sector

5.2.4.3 Losses by location

Figure 63 and Figure 64 present the AAL maps by location for the communications sector. Rainfall-triggered landslides are not included, as the affected locations are in rural areas far from the canton's urban area.

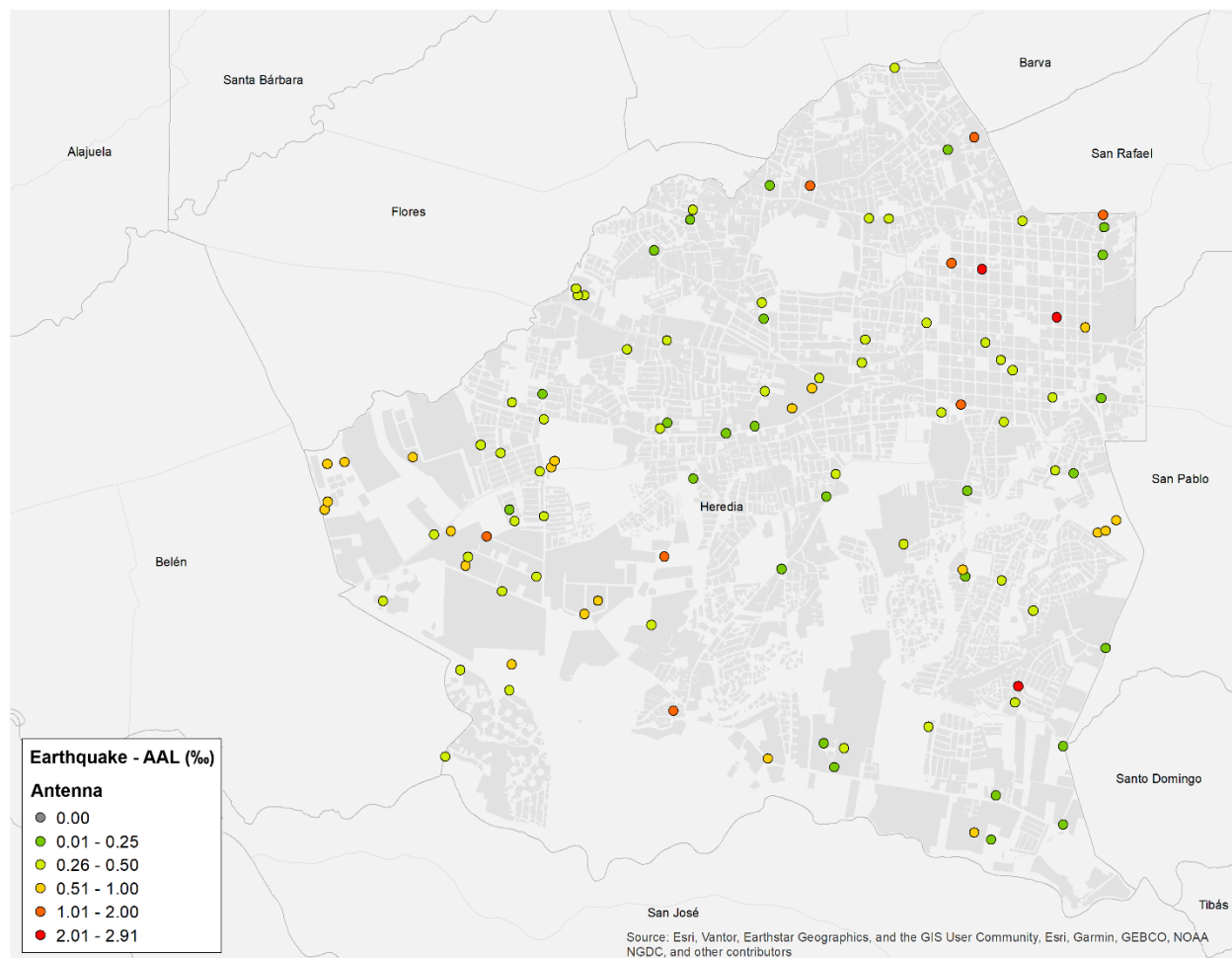


Figure 63. Average Annual Loss due to earthquakes for the communications sector in the canton of Heredia

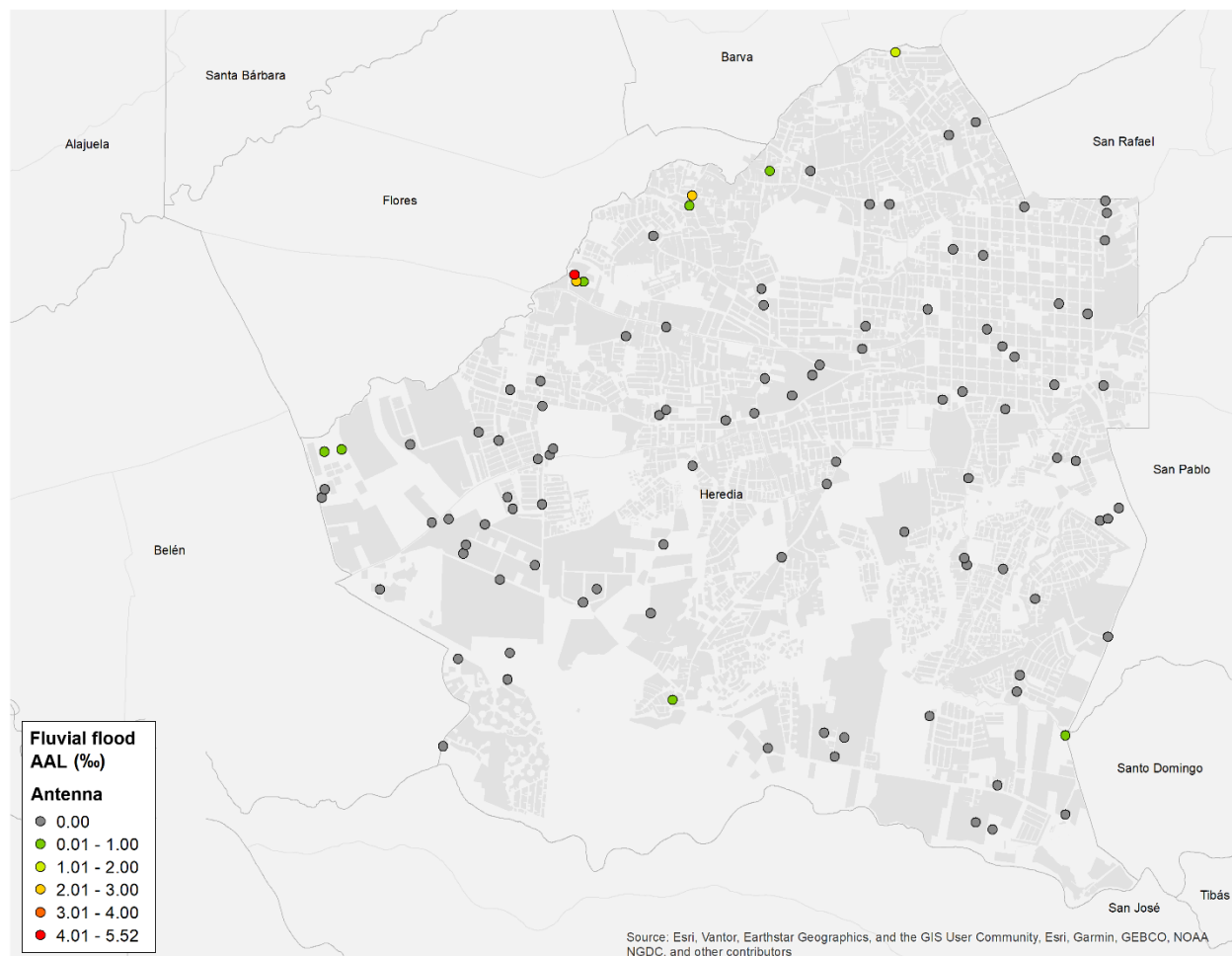


Figure 64. Average Annual Loss due to fluvial flooding for the communications sector in the canton of Heredia

The AAL maps by location for the communications sector show that expected seismic losses tend to concentrate in a limited number of sites, reflecting the point-based nature of the antenna portfolio within the canton. Since these infrastructures are typically located strategically in elevated areas or at specific coverage nodes, the spatial pattern of seismic risk is not diffused but rather structured around discrete sites where most of the exposed value and, consequently, the expected annual contribution are concentrated.

In the case of fluvial flood, the corresponding map shows an even more localized impact, restricted to antennas located near river corridors or low-lying areas susceptible to overflow.

5.2.5 Water and sanitation sector

For the water and sanitation sector, results are presented separately for drinking water and wastewater systems.

5.2.5.1 Average Annual Loss (AAL)

Table 16 presents the AAL values for the drinking water sector, while Table 17 presents these values for the wastewater sector, this AAL values reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided. In order to limit the length of the document, only the baseline climate and the climates that produce the maximum and minimum AAL for hydrometeorological hazards are presented. Figure 65 and Figure 66 show the same information graphically.

Table 16. Average Annual Loss by hazard and climate scenario in the drinking water sector. Values in millions of Costa Rican colones (CRC).

Portfolio		Sources		Storage tanks		Pumping systems		Water supply network . pipelines		Hydrants	
Exposed value		\$4,459,000,000		\$3,559,872,800		\$1,069,286,400		\$33,238,208,100.00		\$673,965,600	
Ame.	Esc.	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)
Earthquake		\$2,233,336	0.50	\$2,752,957	0.77	\$1,406,269	1.32	\$355,012	0.01	\$0	0.00
Fluvial flood	Base	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2035	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2035	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2050	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2050	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2100	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2100	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
Pluvial flood	Base	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2035	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2035	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2050	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2050	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Min. 2100	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
	Max. 2100	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00	\$0	0.00
Earthquake-triggered landslides		\$3,114,705	0.70	\$56,883	0.02	\$242,538	0.23	\$2,504,159	0.08	\$18,830	0.03
Rainfall-triggered landslides	Base	\$9,012,502	2.02	\$169,296	0.05	\$705,435	0.66	\$8,646,102	0.26	\$69,558	0.10
	Min. 2035	\$9,006,922	2.02	\$169,544	0.05	\$711,012	0.66	\$8,688,793	0.26	\$69,631	0.10
	Max. 2035	\$10,610,792	2.38	\$197,067	0.06	\$816,574	0.76	\$8,948,997	0.27	\$72,065	0.11
	Min. 2050	\$9,234,037	2.07	\$175,342	0.05	\$744,687	0.70	\$8,471,146	0.25	\$74,376	0.11
	Max. 2050	\$12,424,654	2.79	\$263,399	0.07	\$1,211,223	1.13	\$10,959,383	0.33	\$61,318	0.09
	Min. 2100	\$8,732,847	1.96	\$206,982	0.06	\$699,835	0.65	\$8,846,279	0.27	\$69,514	0.10
	Max. 2100	\$14,126,302	3.17	\$267,066	0.08	\$1,127,511	1.05	\$10,915,634	0.33	\$57,174	0.08

Table 17. Average Annual Loss by hazard and climate scenario in the wastewater sector. Values in millions of Costa Rican colones (CRC)

Portfolio		Sewer network – collectors		Manholes		Treatment plants	
<i>Exposed value</i>		\$11,425,048,700		\$1,955,178,000		\$162,500,000	
Hazard	Esc.	AAL	AAL (‰)	AAL	AAL (‰)	AAL	AAL (‰)
<i>Earthquake</i>		\$143,416	0.01	\$433,504	0.22	\$164,447	1.01
<i>Fluvial flood</i>	<i>Base</i>	\$0	0.00	\$0	0.00	\$147,308	0.91
	<i>Min. 2035</i>	\$0	0.00	\$0	0.00	\$138,022	0.85
	<i>Max. 2035</i>	\$0	0.00	\$0	0.00	\$173,057	1.06
	<i>Min. 2050</i>	\$0	0.00	\$0	0.00	\$135,323	0.83
	<i>Max. 2050</i>	\$0	0.00	\$0	0.00	\$190,875	1.17
	<i>Min. 2100</i>	\$0	0.00	\$0	0.00	\$121,397	0.75
	<i>Max. 2100</i>	\$0	0.00	\$0	0.00	\$177,329	1.09
<i>Pluvial flood</i>	<i>Base</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Min. 2035</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Max. 2035</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Min. 2050</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Max. 2050</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Min. 2100</i>	\$0	0.00	\$0	0.00	\$0	0.00
	<i>Max. 2100</i>	\$0	0.00	\$0	0.00	\$0	0.00
<i>Earthquake-triggered landslides</i>		\$267,155	0.02	\$50,947	0.03	\$82,093	0.51
<i>Rainfall-triggered landslides</i>	<i>Base</i>	\$1,112,716	0.10	\$226,538	0.12	\$380,401	2.34
	<i>Min. 2035</i>	\$1,071,892	0.09	\$218,257	0.11	\$365,199	2.25
	<i>Max. 2035</i>	\$1,169,338	0.10	\$238,975	0.12	\$397,203	2.44
	<i>Min. 2050</i>	\$981,234	0.09	\$200,138	0.10	\$334,419	2.06
	<i>Max. 2050</i>	\$1,186,978	0.10	\$242,991	0.12	\$403,920	2.49
	<i>Min. 2100</i>	\$675,548	0.06	\$138,357	0.07	\$230,291	1.42
	<i>Max. 2100</i>	\$1,196,279	0.10	\$245,081	0.13	\$406,578	2.50

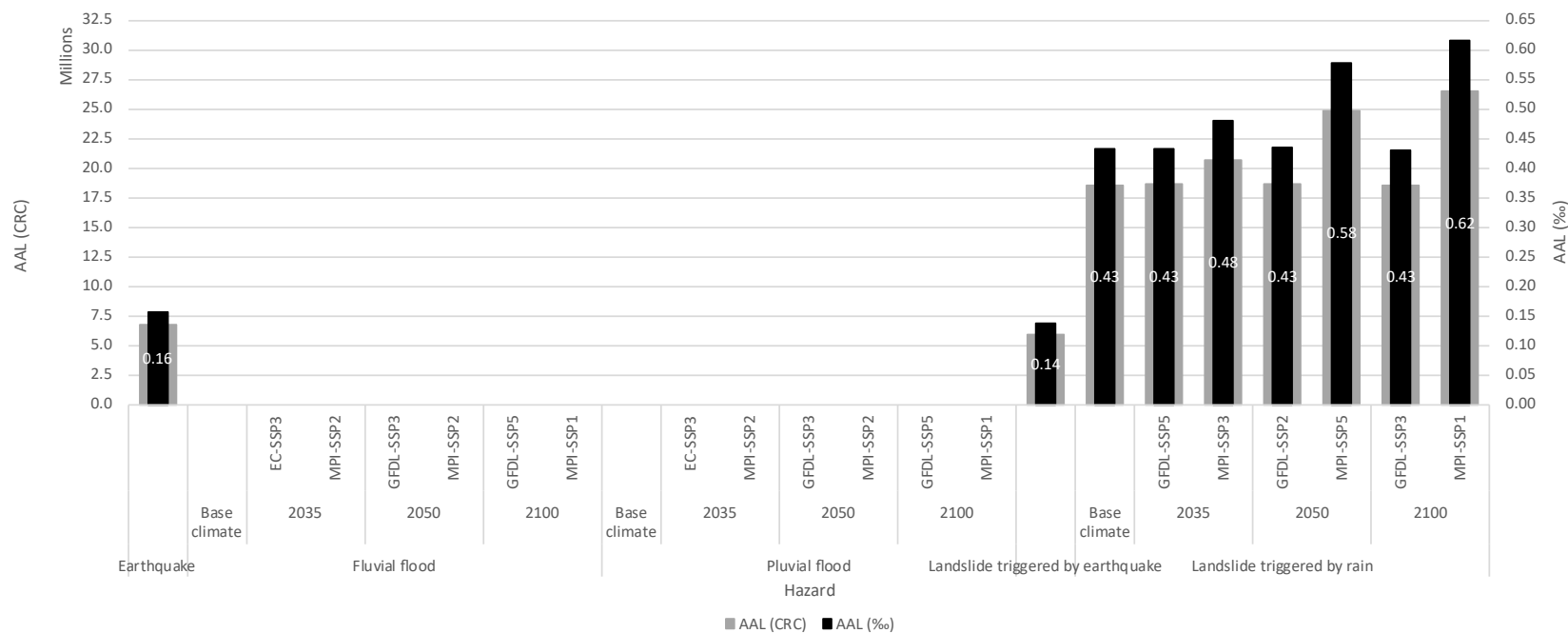


Figure 65. Average Annual Loss by hazard for the drinking water sector

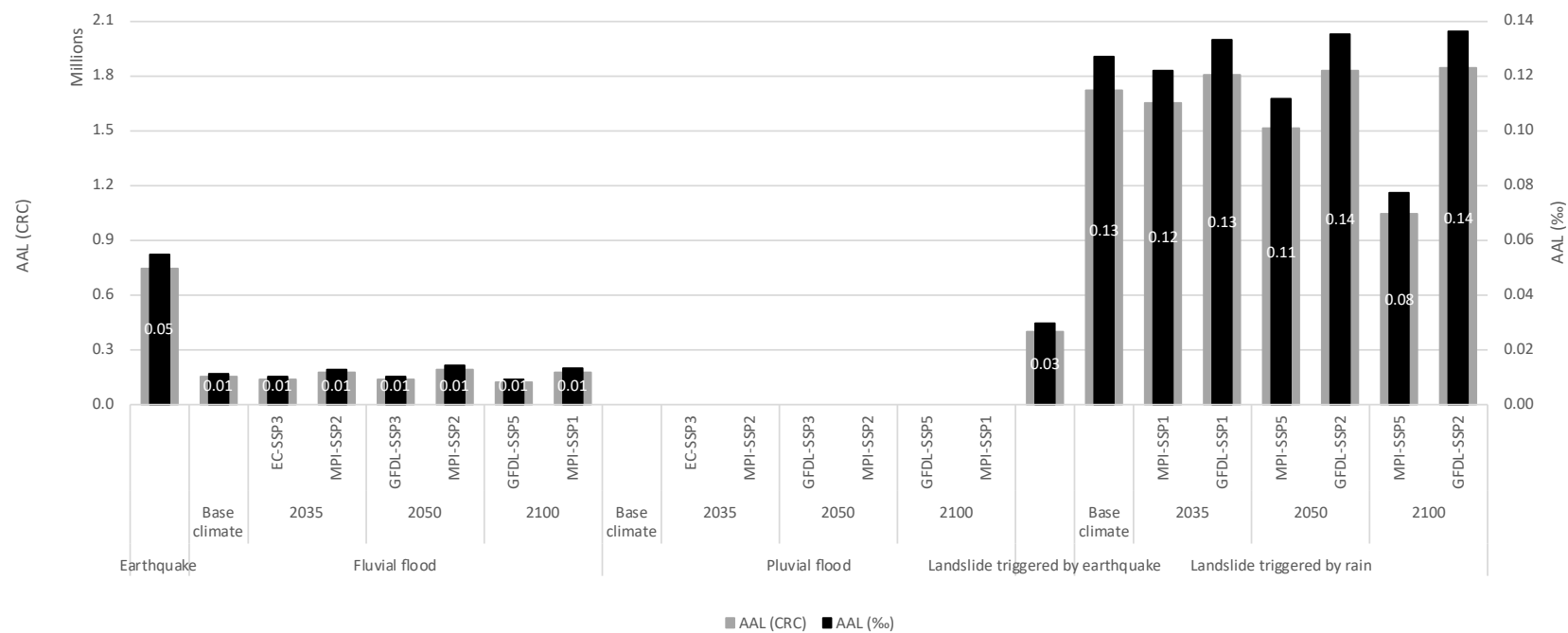


Figure 66. Average Annual Loss by hazard for the wastewater sector

The AAL results for the drinking water subsector show a profile dominated by mass movement processes, with secondary contributions from direct earthquake effects. For storage tanks, the expected annual losses from rainfall-triggered landslides reach values close to CRC 9.0 million, increasing up to CRC 14.1 million under the maximum climate scenario considered, representing relatively high losses on the order of 2.0–3.2‰. A similar pattern is observed in the water supply network (pipelines) and in pumping systems, although with smaller magnitudes. In contrast, earthquakes contribute more moderate but consistent annual losses across all components, with notable values in pumping systems (CRC 2.75 million, $\approx 0.77\%$) and storage tanks (CRC 2.23 million, $\approx 0.50\%$). Fluvial and pluvial flood hazards are null in this subsector, indicating the absence of modeled losses from these mechanisms.

In the case of the wastewater subsector, expected losses present lower absolute magnitudes in the collector network and manholes, but with relevant contributions in treatment plants, both from fluvial flood and rainfall-triggered landslides. Seismic AAL is low for collectors (CRC 0.14 million) and manholes (CRC 0.43 million), while in treatment plants it reaches CRC 0.16 million ($\approx 1.01\%$), reflecting a higher relative vulnerability of the point asset component. For fluvial flood, only treatment plants present non-zero expected losses, with baseline values of CRC 0.15 million and a climatic range up to CRC 0.19 million. Rainfall-triggered landslides constitute the main annual mechanism in this subsector, especially in treatment plants ($\approx$ CRC 0.38–0.41 million, up to $\approx 2.5\%$ relative), highlighting a significant sensitivity to future climate scenarios.

As with the communications portfolio, although the loss values are relatively low, they should not be considered negligible, since they reflect only the physical component of the assets evaluated and do not account for potential fluctuations or disruptions in the services provided.

5.2.5.2 Probable Maximum Loss (PML)

Figure 67 shows the PML curves for the drinking water sector, and Figure 68 shows the curves for the wastewater sector, under the hazards considered.

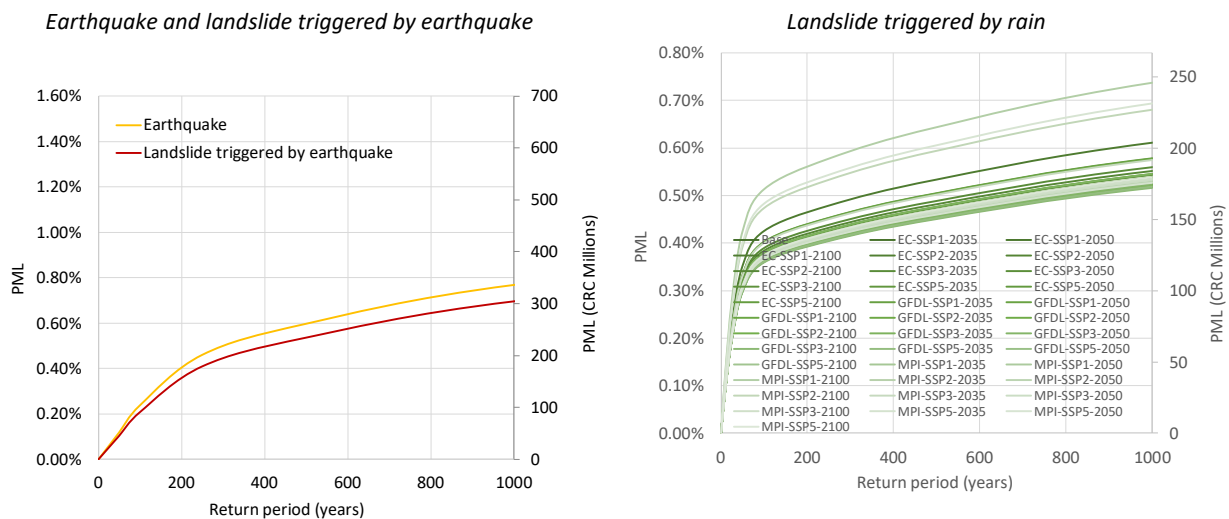


Figure 67. PML curves for all considered hazards and all climate scenarios – Drinking water sector

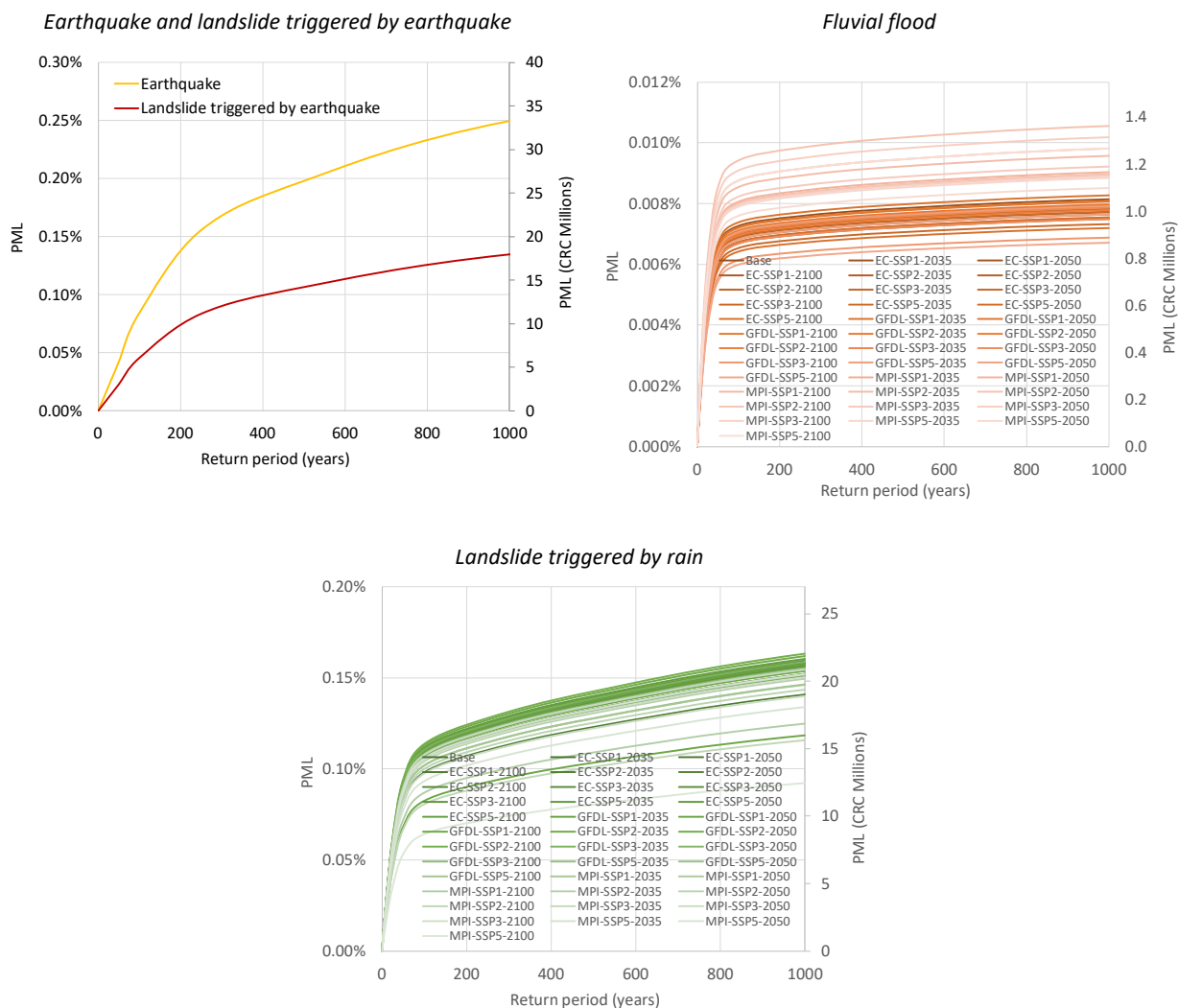


Figure 68. PML curves for all considered hazards and all climate scenarios – Wastewater sector

The PML curves for drinking water reflect a limited set of relevant hazards, where extreme risk is primarily controlled by rainfall-triggered landslides and, to a lesser extent, by seismic events. Direct earthquakes show a curve with progressive growth toward longer return periods. However, shaking-induced landslides introduce an additional exceedance component, particularly associated with critical segments of the linear system. For rainfall-triggered landslides, the overlap of curves corresponding to the 36 alternative climate scenarios generates a wide spread of exceedance losses, with noticeable shifts in maximum scenarios toward higher losses at long return periods.

In the wastewater subsector, the PML curves additionally incorporate fluvial flooding as a relevant mechanism, although mainly concentrated in treatment plants. In this case, the climatic dispersion for fluvial flood is moderate, remaining within a bounded range of extreme losses. On the other hand, rainfall-triggered landslides again show the largest separation among climate scenarios, highlighting a high sensitivity of the loss tails to future hydrometeorological conditions. Direct seismic hazard maintains a

secondary role in terms of absolute extreme magnitudes, but still contributes consistent exceedance losses due to the distributed exposure of collectors and manholes within the urban system.

5.2.5.3 Losses by location

Figure 69 to Figure 71 present the AAL maps by location for the drinking water sector, while Figure 72 to Figure 75 present the maps for the wastewater sector.

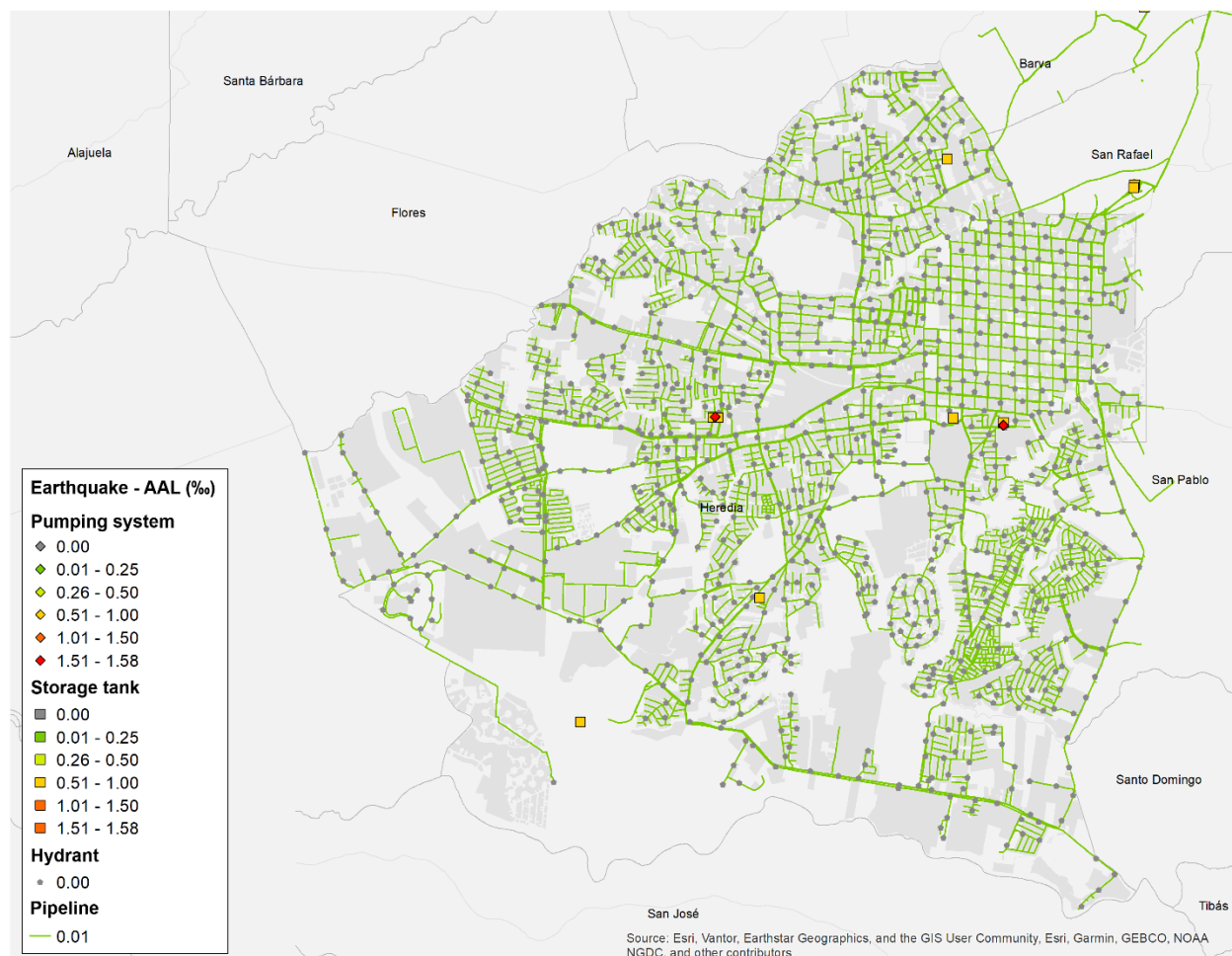


Figure 69. Average Annual Loss due to earthquake for the drinking water sector in the canton of Heredia

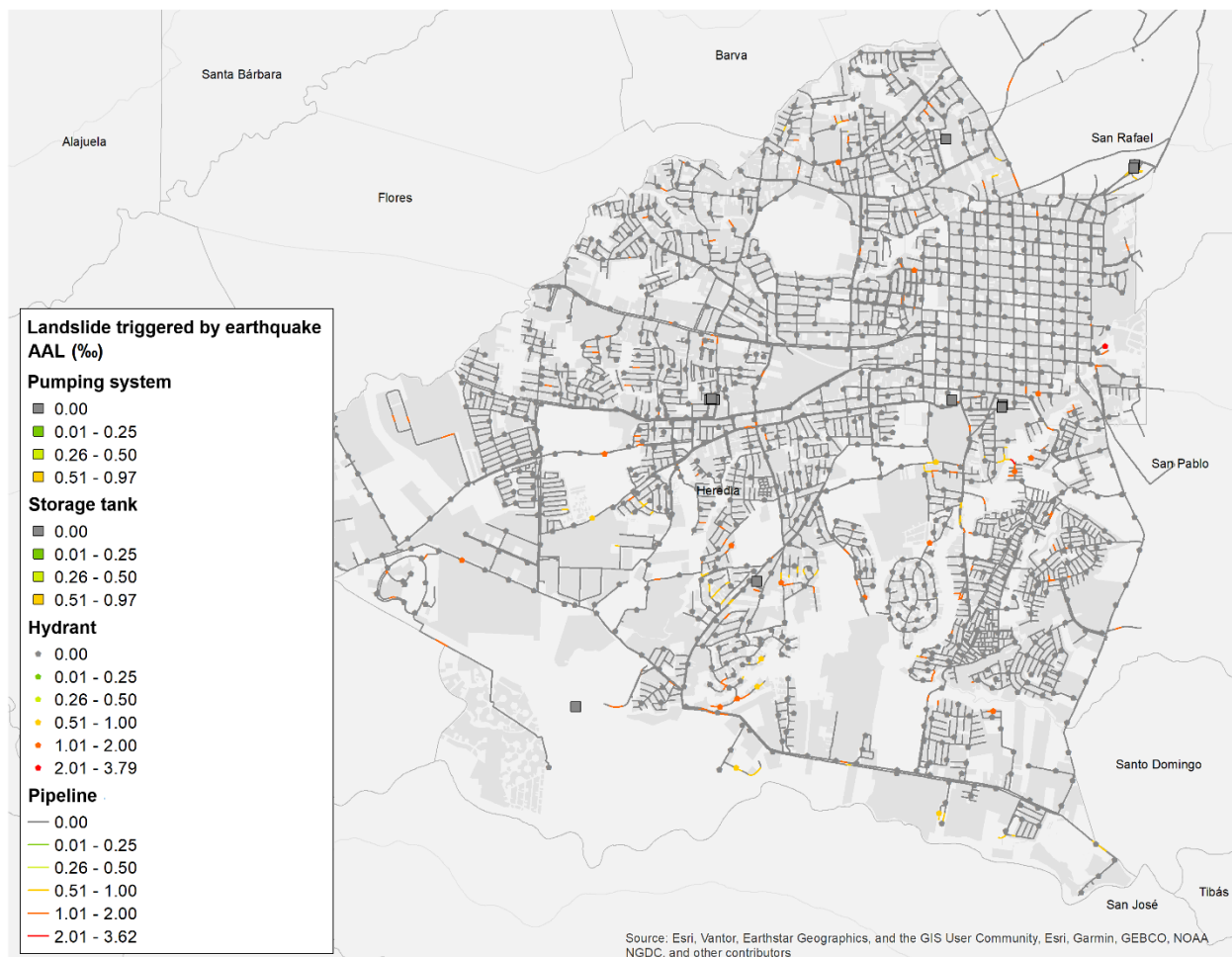


Figure 70. Average Annual due to earthquake-triggered landslides for the drinking water sector in the canton of Heredia

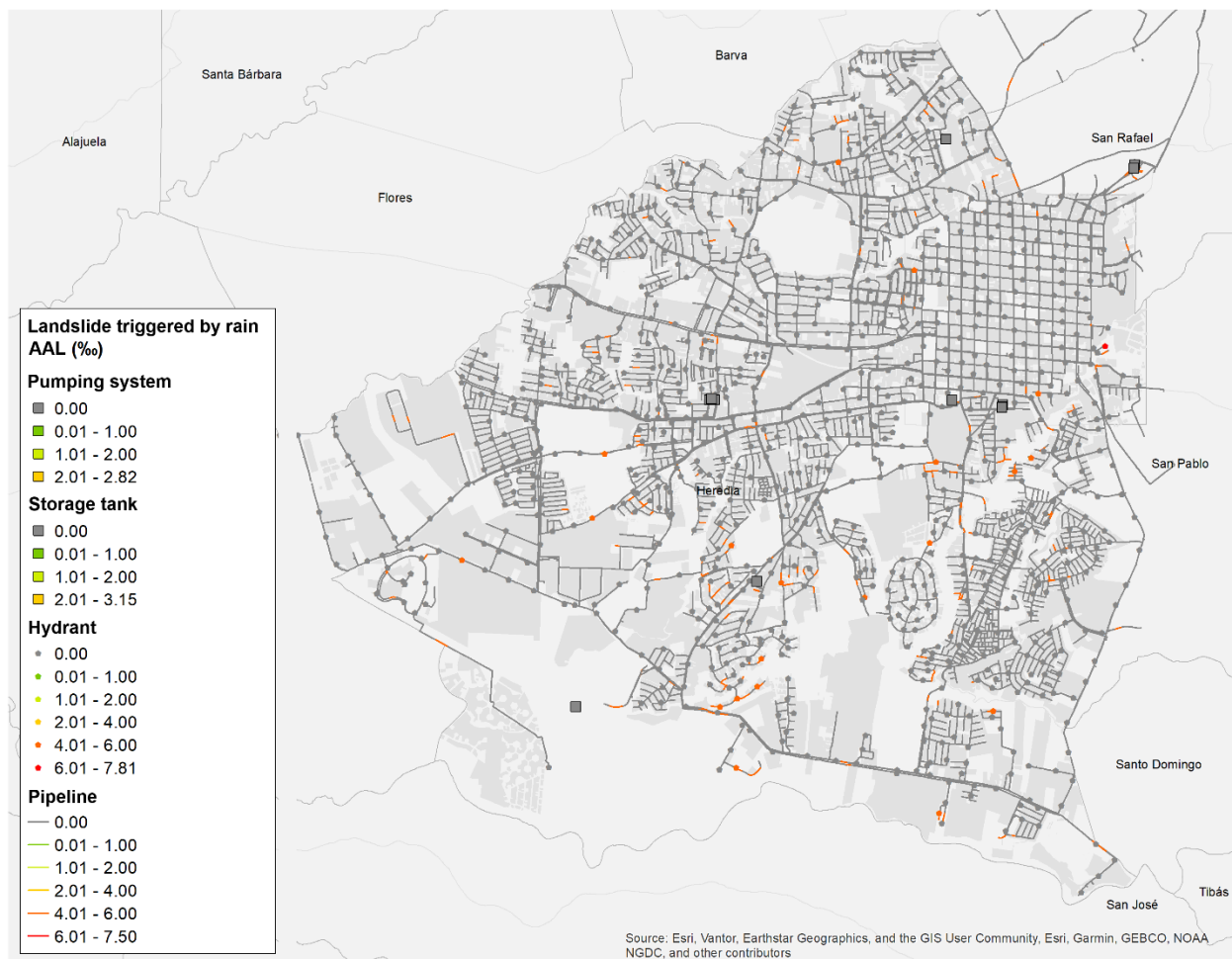


Figure 71. Average Annual Loss due to rainfall-triggered landslides for the drinking water sector in the canton of Heredia

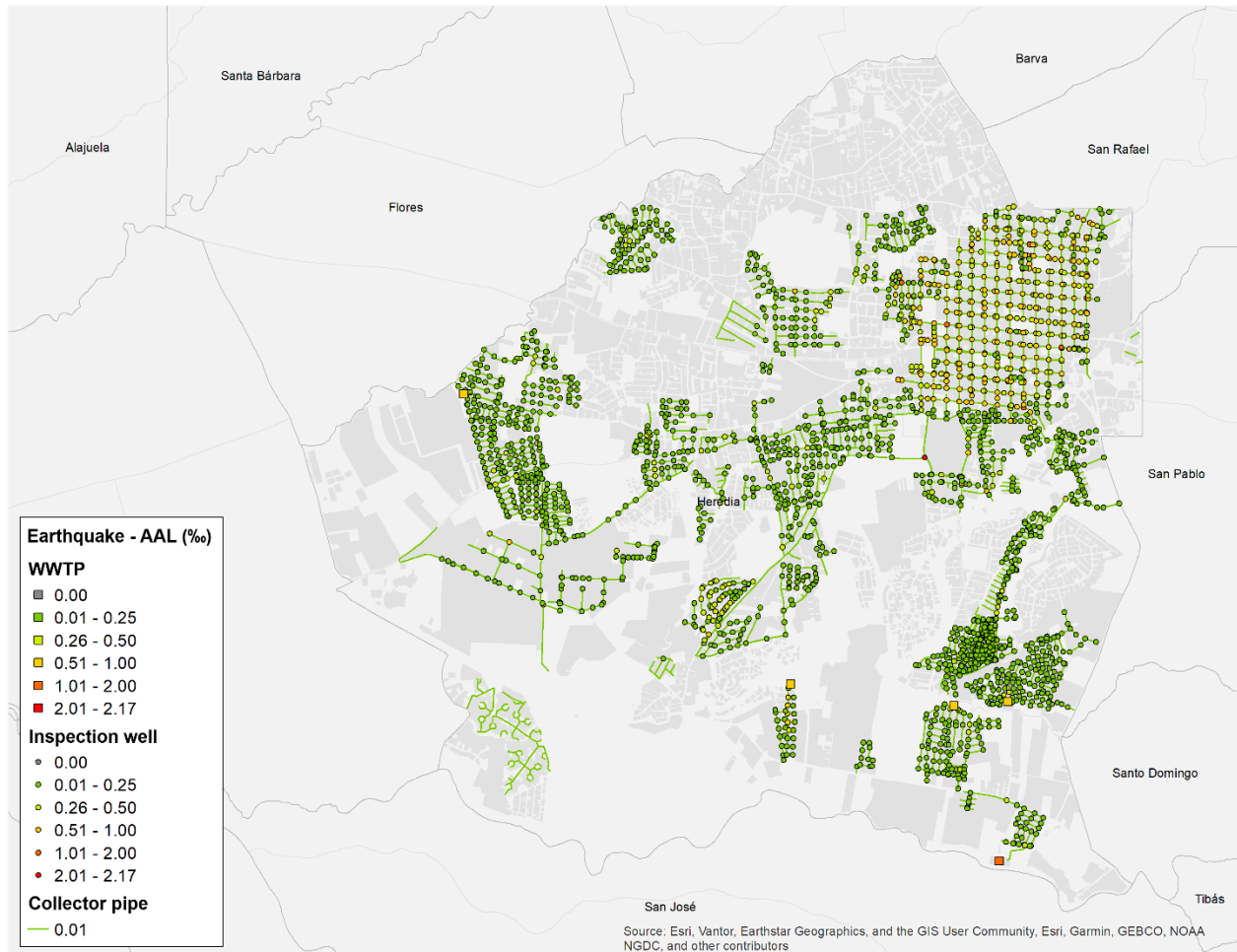


Figure 72. Average Annual Loss due to earthquakes for the wastewater sector in the canton of Heredia

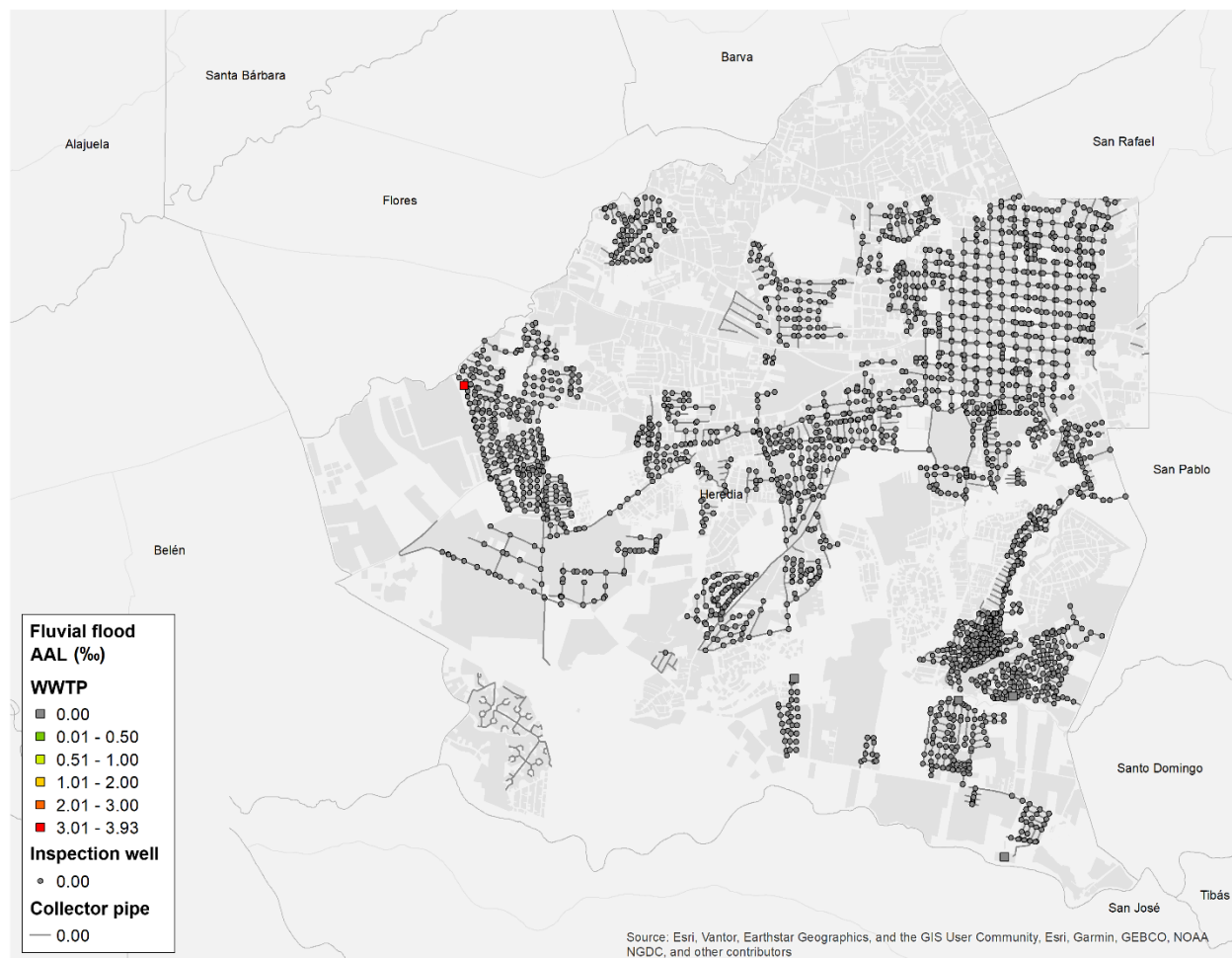


Figure 73. Average Annual Loss due to fluvial flood for the wastewater sector in the canton of Heredia

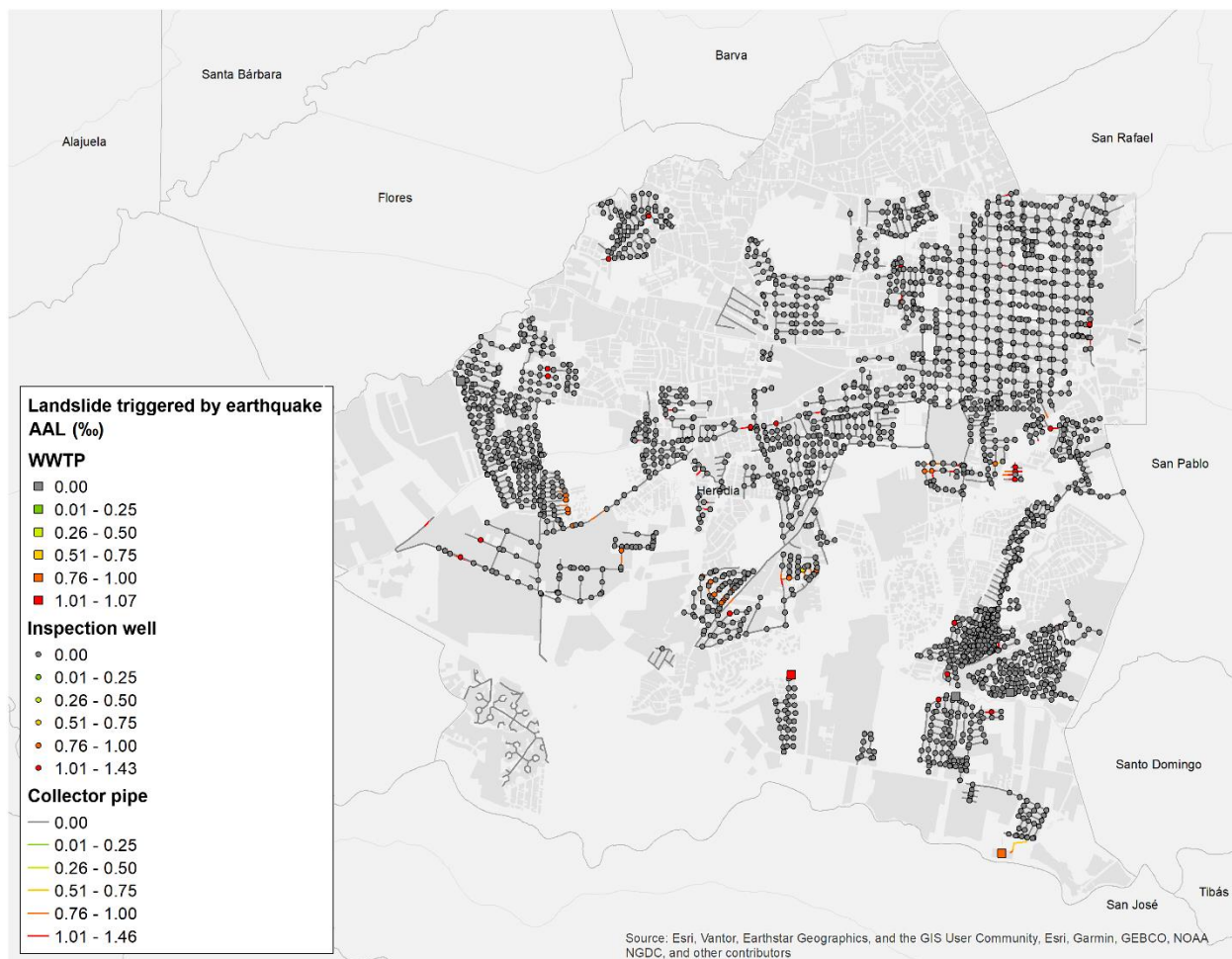


Figure 74. Average Annual Loss due to earthquake-triggered landslides for the wastewater sector in the canton of Heredia

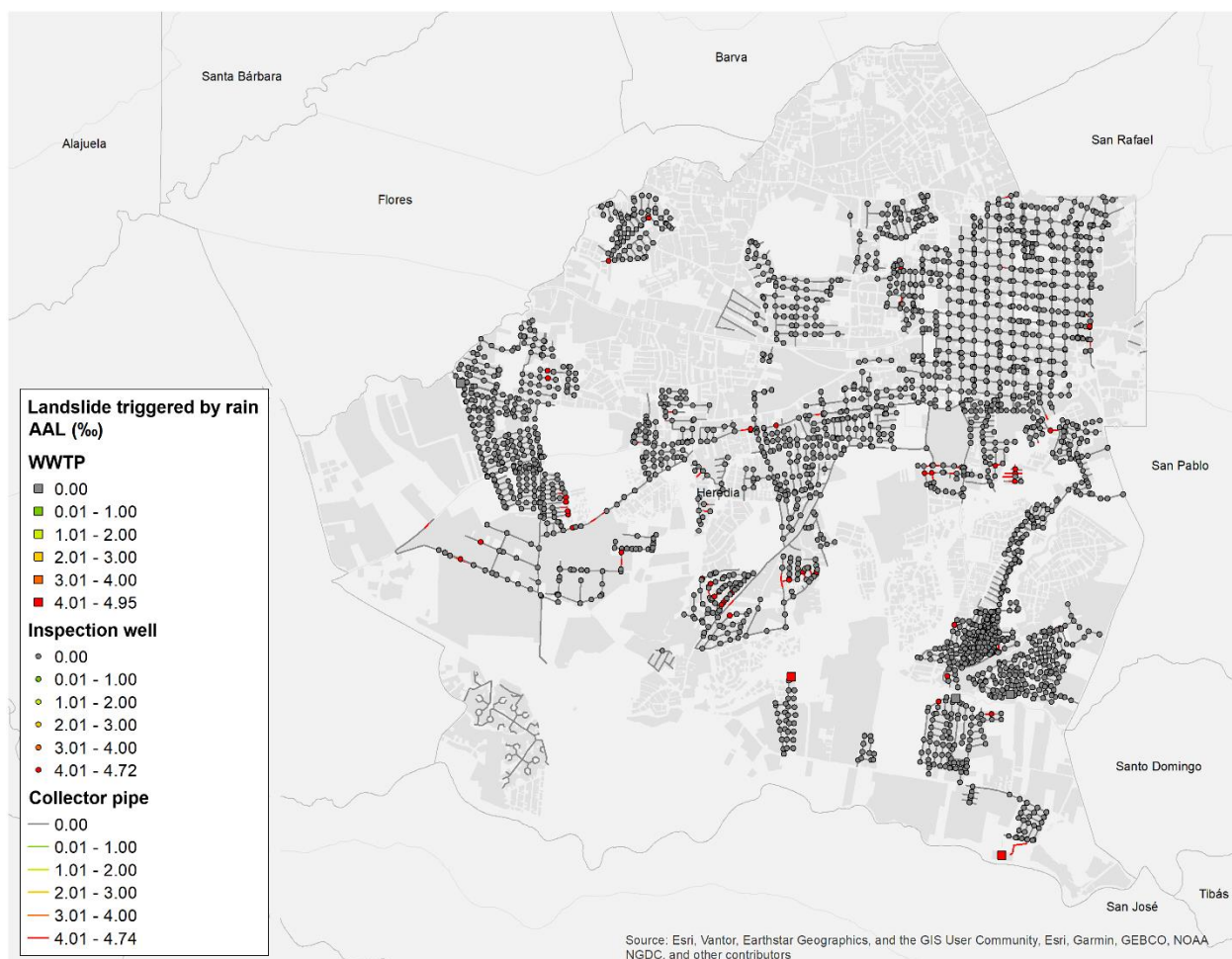


Figure 75. Average Annual Loss due to rainfall-triggered landslides for the wastewater sector in the canton of Heredia

The AAL maps by location for the drinking water sector show a highly segmented spatial pattern, where seismic losses and landslide-induced losses are concentrated at specific sites associated with storage tanks, pumping stations, and vulnerable segments of the network. In particular, the maps of rainfall-triggered landslides reveal dominant clusters in hillside areas within the canton.

For the wastewater sector, the mapping reveals a more pronounced differentiation between linear and point components. Collectors show seismic losses distributed relatively continuously, while treatment plants simultaneously concentrate relevant clusters of fluvial flood, earthquake-triggered landslides, and rainfall-triggered landslides. In this subsector, the maps make it possible to identify how annual risk is structured by a small number of point facilities with high relative loss, combined with an extensive linear exposure network with lower unit contributions. The coexistence of hydrological patterns (fluvial flood) and geomorphological patterns (landslides) is particularly evident in the locations of the highest expected annual losses.

5.2.6 Variability in Risk Metrics under Future Climate Scenarios

The AAL results presented above are limited to illustrating risk primarily in terms of the baseline climate, or the set of climate scenarios producing the highest and lowest losses, in order to avoid overloading the document. However, it is useful to examine the aggregate AAL totals for all hydrometeorological hazards across all infrastructure sectors, including the full set of climate scenarios.

Figure 76 to Figure 79 show the total AAL (all sectors) as a function of time for fluvial flooding, pluvial flooding, and rainfall-triggered landslides. Each line in the graphs corresponds to a different climate projection, that is, a combination of GCM model and emissions pathway. In this way, it is possible to observe the temporal evolution of flood and rainfall-triggered landslide risk when considering different climate models.

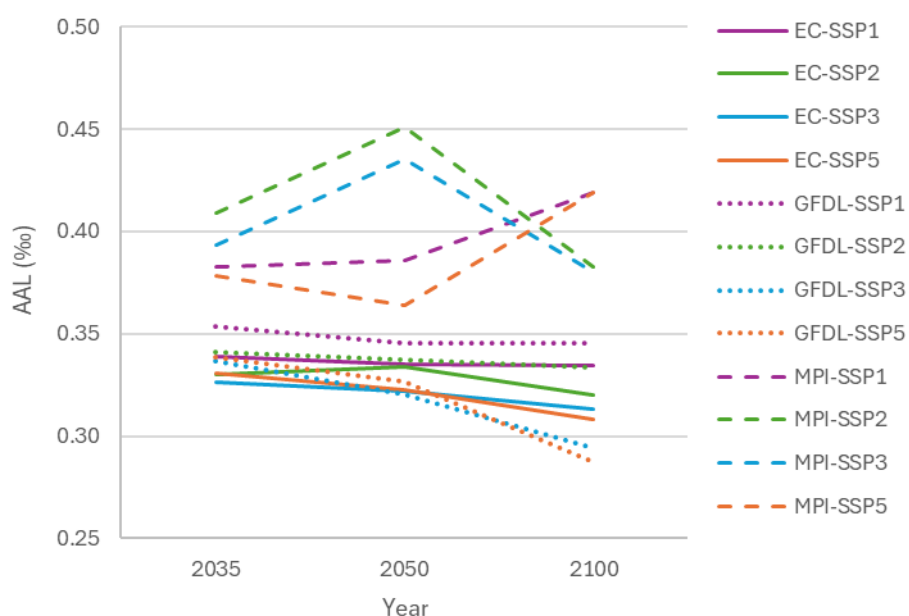


Figure 76. Total Average Annual Loss of infrastructure due to fluvial flood for the considered climate change scenarios

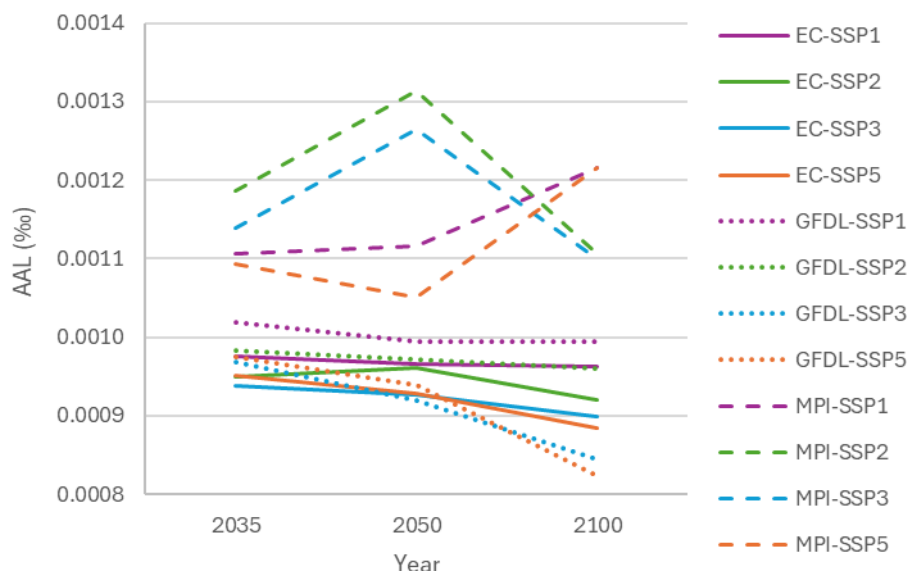


Figure 77. Total Average Annual Loss of infrastructure due to pluvial flood for the considered climate change scenarios

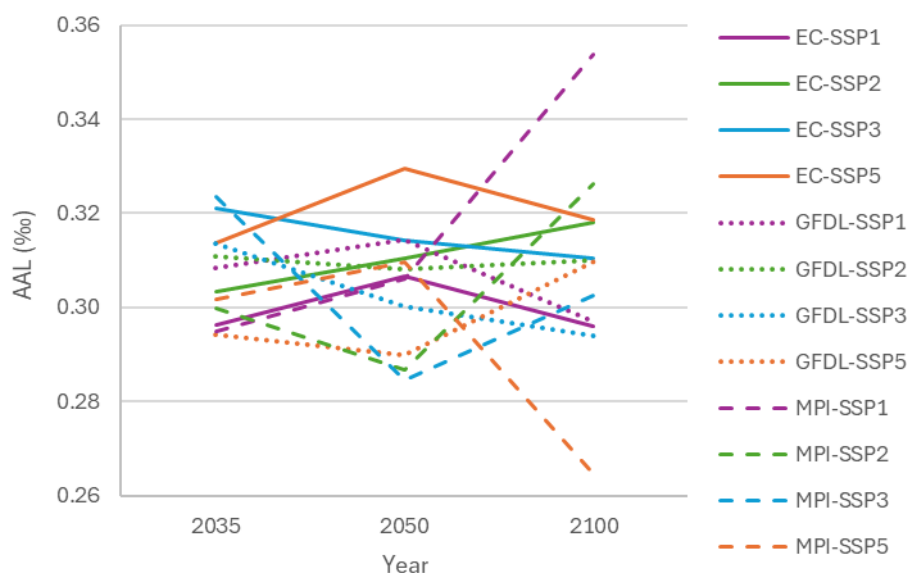


Figure 78. Total Average Annual Loss of infrastructure due to rainfall-triggered landslides for the considered climate change scenarios

In the case of fluvial flood, the total AAL presents values on the order of ~0.32–0.45‰, with a clear differentiation among climate models. The set of EC and GFDL simulations shows relatively stable or slightly decreasing trends toward 2100, with moderate reductions in several SSP scenarios, particularly those with higher forcing (SSP5). In contrast, the MPI realizations exhibit much greater temporal

sensitivity, with marked increases toward 2050 in SSP2 and SSP3 (reaching maximum close to 0.45‰) and subsequently decreasing toward 2100. This behavior indicates that, at the aggregate portfolio scale, the response of projected fluvial risk is dominated more by model dispersion than by a monotonic evolution, showing that certain GCMs concentrate relevant transient increases at intermediate horizons. For pluvial flood, the total AAL is considerably lower in absolute magnitude ($\approx 0.00085\text{--}0.00130\%$), confirming that even when aggregating all sectors, this mechanism remains a secondary contributor compared with fluvial flood.

Regarding rainfall-triggered landslides, the total AAL falls within an intermediate range ($\sim 0.29\text{--}0.35\%$) and shows the most irregular temporal pattern among the three mechanisms. Unlike flooding hazards, no consistent directional trend toward increases or decreases over time is observed: some scenarios show increases toward 2050 followed by reductions, while others display pronounced increases only toward 2100, such as MPI-SSP1, which reaches the maximum values of the set. Additionally, scenarios with abrupt decreases toward the end of the century can be identified, such as MPI-SSP5. This behavior indicates that, for the aggregate portfolio, risk from rainfall-induced mass movements is controlled by a more complex combination of climatic and spatial factors, with nonlinear and divergent responses across climate models and emissions pathways.

5.3 Result Verification

Probabilistic modeling of catastrophic risk is based on the integration of available information on hazard, exposure, and vulnerability, combined with technical assumptions that allow complex phenomena to be represented in the absence of complete observations. This approach aims to characterize, in a stochastic manner, the potential consequences of future events whose occurrence is scientifically plausible but that have not necessarily occurred in the territory being evaluated. In this sense, the results obtained do not constitute a direct extrapolation of historical experience, but rather an analytical construction designed to estimate low-frequency, high-severity impacts that exceed the range normally documented in disaster records.

Under these conditions, strict validation of risk results, understood as the ability to statistically compare simulated losses against a sufficient set of empirical observations in order to evaluate the model's fit, is not feasible. Robust validation would require extensive and detailed loss databases covering a wide spectrum of hazard intensities, with systematic information at the individual asset level, including specific construction typologies and the exact levels of demand experienced in each event. This type of evidence does not exist and is unlikely to exist in the future, as it would require the repeated occurrence of severe events under comparable conditions, together with a level of instrumentation and documentation that has historically not existed even in the most advanced risk management contexts.

Given this reality, an alternative procedure for verifying the results of the assessment is proposed, based on the concept of the hybrid risk curve (Velázquez, 2014). The hybrid curve is a loss exceedance curve composed of two segments. The first segment is obtained empirically, based on information documented in historical disaster databases (See annex A. 1), and provides a retrospective view of risk for the evaluated portfolio. The second segment corresponds to the analytical loss exceedance curve, evaluated through

catastrophe modeling such as that implemented in this study, and provides a prospective view of disaster risk. The envelope of both curves constitutes the hybrid risk curve. Figure 79 illustrates these curves⁴.

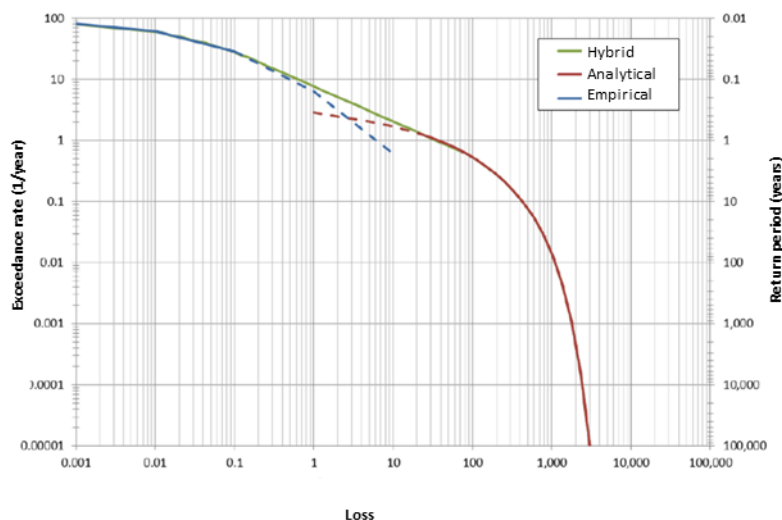


Figure 79. Illustration of analytical, empirical, and hybrid Loss Exceedance Curves. Adapted from Velázquez (2014).

The hybrid risk curve has been used in the past as a complement to risk modeling through analytical assessment, with the purpose of capturing losses from very frequent events that may fall outside the scope and resolution of catastrophe models. Likewise, this approach provides insight into the ability of the analytical model to describe losses recorded in historical data. As shown in Figure 79, the capacity of the empirical model to correctly represent the exceedance rates of large losses is limited, just as the analytical model has limited capacity to appropriately represent the exceedance rates of smaller events. For this reason, it is common for both curves to overlap (although this is not a necessary condition).

The overlap zone provides information on the extent to which the analytical model is capable of describing at least a portion of the historical losses. This characteristic can be used as a validation process, given the limitations previously mentioned.

Figure 80 shows two hypothetical cases of hybrid exceedance curves. In the first case, the analytical curve matches the empirical curve sufficiently well, meaning that the catastrophe model shows a certain capacity to represent historically recorded losses. In contrast, the second hybrid curve illustrates how the catastrophe model fails to appropriately reproduce the exceedance rates of losses observed in the historical record. In other words, the model does not properly capture risk within the overlap zone (and in this particular example, it underestimates it).

However, this does not necessarily imply a deficiency of the analytical model, since these models are designed to capture information about events that have not yet occurred, but rather illustrates the

⁴ Throughout this section of the document, the loss exceedance curves are presented in logarithmic scale plots in order to facilitate visualization.

model's ability—or lack thereof—to reproduce historical behavior. It is important to keep in mind that, in catastrophe modeling, reproducing historical events is never the primary objective of the models.

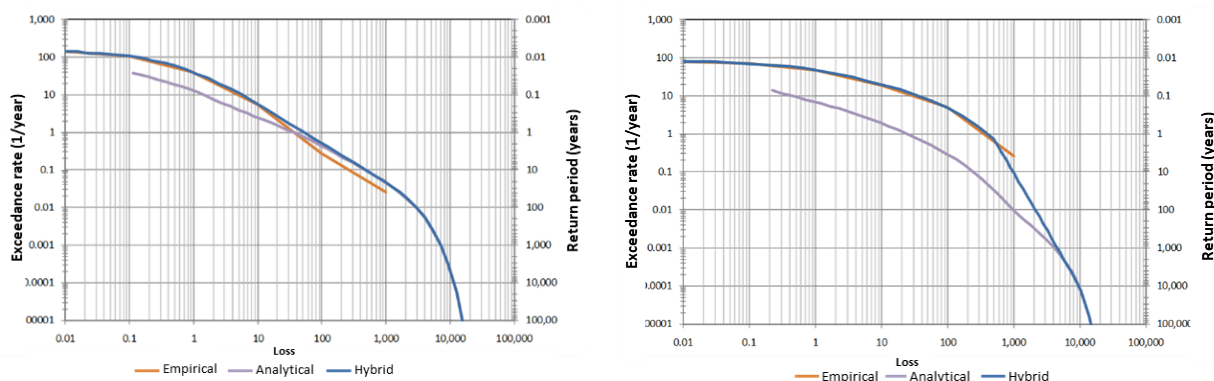


Figure 80. Examples of hybrid risk curves. The curve on the left corresponds to a valid analytical model, and the one on the right to a non-valid model, in terms of its ability to reflect historical losses.

As is evident, this alternative validation procedure can only be applied if a reliable and complete loss record exists, providing information for the historical period from which the empirical risk curve can be derived. If such a record does not exist, or if the available data are insufficient or unreliable, it would not be possible to carry out this verification.

5.3.1 Disaster Database of Costa Rica

Three potential sources of retrospective information on historical losses caused by natural events were consulted: the international EM-DAT database, the regional DesInventar system, and the national loss module administered by the Ministry of National Planning and Economic Policy (MIDEPLAN). Based on this review, it was identified that, for the specific case of Costa Rica, the institutional database managed by MIDEPLAN provides the most complete and systematic record, in terms of territorial coverage, sectoral disaggregation, and consistency in the documentation of losses associated with officially declared emergencies. It therefore constitutes the most robust repository available for characterizing historical economic impacts of disasters in the country.

Information on losses associated with natural events is structured within the MIDEPLAN Module of Losses Caused by Natural Phenomena. This system consolidates historical records of direct damage and economic losses associated with events that have required official emergency declarations, incorporating information dating back to the late 1980s. The database allows queries and analyses disaggregated by territorial unit and economic sector, constituting an institutional repository for the systematic documentation of the impacts of natural hazards such as floods, landslides, droughts, earthquakes, and other relevant phenomena in the national context.

5.3.2 Evaluation of the Empirical Risk Curve

The empirical loss exceedance curve is obtained directly from the information recorded in the MIDEPLAN database, based on an exceedance count of arbitrary loss levels. The historical record can be interpreted as an observation of a loss process, such as the one illustrated in Figure 81. By defining an arbitrary economic loss level p , all events whose losses exceed p can be identified in the graph.

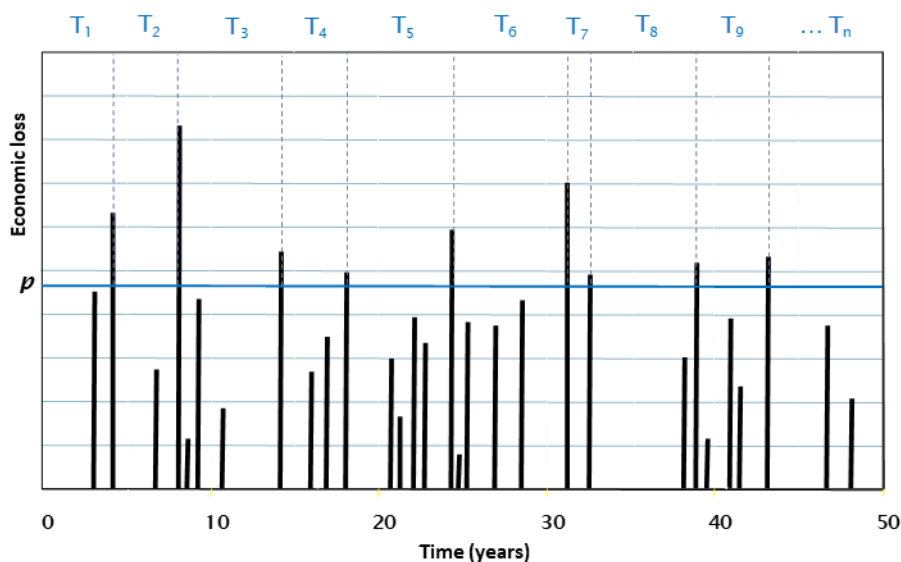


Figure 81. Hypothetical loss process.

For the specified loss level p , the exceedance rate ($v(p)$) can be estimated as follows (Bernal et al., 2021):

$$v(p) = \frac{n - 1}{T} \quad \text{Equation 12}$$

where n is the number of events that exceed loss level p , and T is the total number of years in the record.

As observed, this estimator of the exceedance rate depends on the number of times the evaluated loss level p is exceeded. This implies an inverse relationship between the uncertainty of the estimate and the number of exceedances. A small loss level will be exceeded many times and, therefore, its estimated exceedance rate will have lower uncertainty than that of a larger loss level, which is exceeded fewer times.

Bernal et al. (2021) determined how the coefficient of variation⁵ (CV) of the exceedance rate changes as a function of the number of exceedances in the record, following the relationship shown in Figure 82.

⁵ The coefficient of variation of a random variable is defined as the ratio of its standard deviation to its mean.

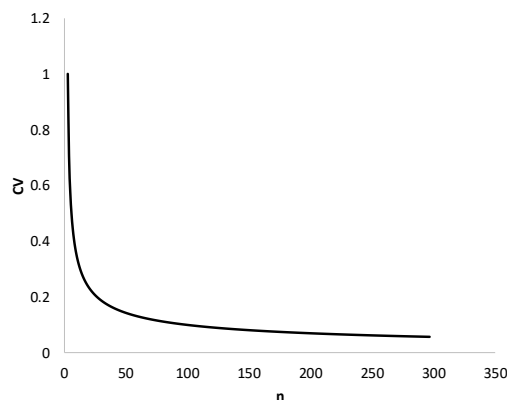


Figure 82. Variation of the coefficient of variation of the exceedance rate as a function of sample size.

The behavior described above shows that, for events involving large losses (catastrophic events), the estimation of the exceedance rate based on the historical record is highly uncertain—that is, there are few events exceeding that loss level, regardless of the quality of the information or even the number of years covered by the record.

This is precisely why analytical loss models are required. By explicitly relating hazard, exposure, and vulnerability, such models allow for a more appropriate estimation of exceedance rates at high loss levels, where historical information is generally insufficient.

Based on this approach to estimating the exceedance rate, constructing the loss exceedance curve becomes straightforward. The process consists of defining different reference loss levels p and calculating the corresponding exceedance rate for each one. Figure 83 presents a diagram summarizing this procedure.

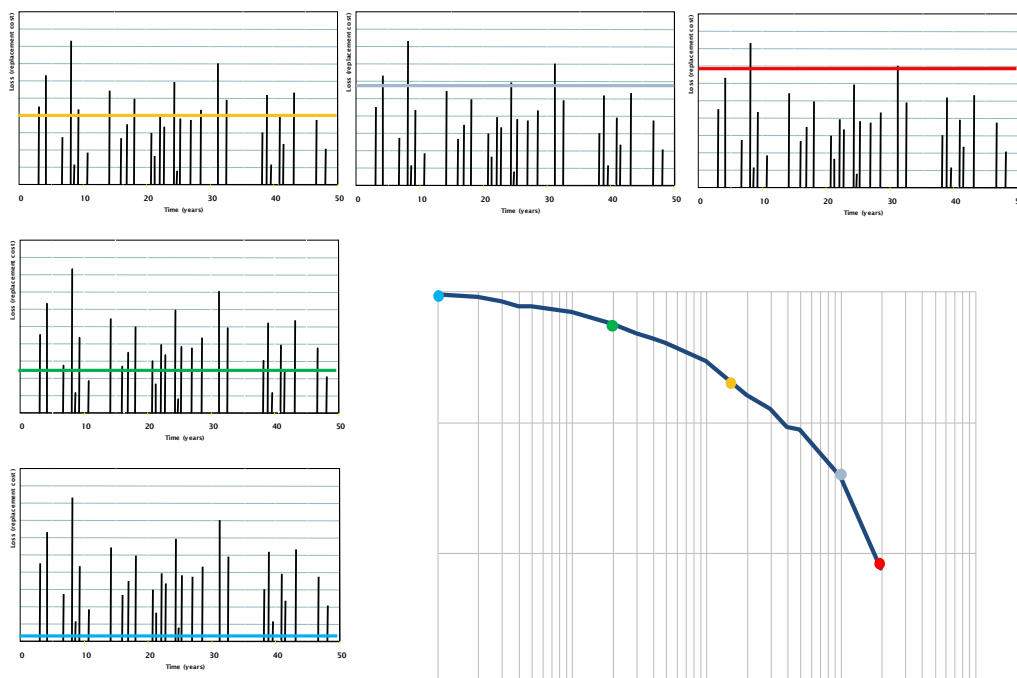


Figure 83. Illustration of the empirical loss exceedance curve evaluation process.

5.3.3 Comparison of the Risk Curve

The procedure described above was applied to the multi-hazard risk results for the canton of Heredia, presented in the previous sections. A total PML curve was obtained, which is converted into an analytical loss exceedance curve directly in accordance with what is indicated in Section 2.3.2.

The empirical curve was obtained by applying the described procedure to the loss records from the MIDEPLAN database associated with events affecting the canton of Heredia. Figure 84 shows the comparison between the empirical and analytical risk curves.

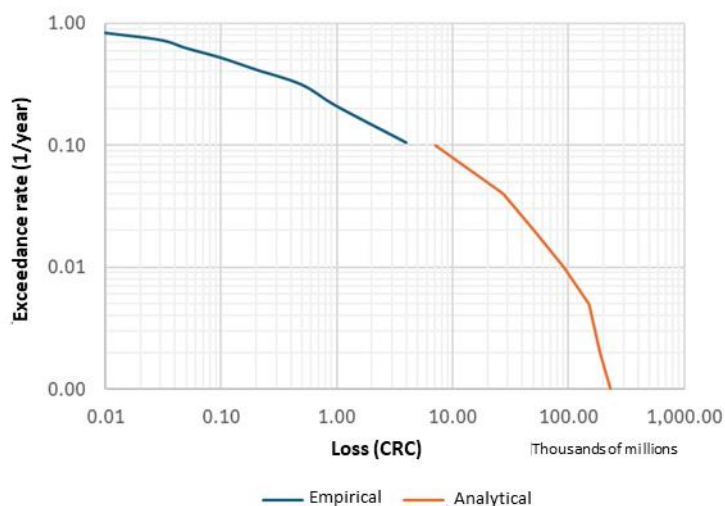


Figure 84. Empirical and analytical Loss Exceedance Curves for Heredia.

It can be observed that, although the curves do not overlap, the agreement between them is very close. It should be emphasized that this should not be interpreted as a strict validation of the results, which is impossible to perform in catastrophe modeling for the reasons previously discussed. Rather, it constitutes a comparison that indicates that the analytical model developed here provides a reasonable extension of the risk metrics when compared with losses observed during the historical period.

6 TRAINING PROGRAM

As part of the Risk Assessment and Capacity Development Project in Costa Rica, implemented within the framework of the Global Risk Modelling Alliance (GRMA), Ingeniar Risk-Intelligence and CIMNE have been developing a comprehensive technical capacity-building process aimed at improving the understanding, application, and use of quantitative risk analysis in the country. This process is primarily structured through the Course on Probabilistic Disaster Risk Modeling, complemented by technical support activities and institutional coordination spaces.

The capacity development approach adopted responds to the guidelines established in the project's Terms of Reference, prioritizing the transfer of technical capabilities for the updating and scalability of risk assessments, as well as strengthening the ability of institutional stakeholders to interpret and use risk information in decision-making, particularly in the context of critical infrastructure in the canton of Heredia.

6.1 Development of Activities

6.1.1 Interpretation of Risk Results and Support for Decision-Making

One of the central objectives of the Strategic Project is to strengthen the capacity of the stakeholders involved to interpret the results of probabilistic risk analyses for fluvial flood, pluvial flood, and earthquakes affecting the critical infrastructure of the canton of Heredia, and to use this information in planning and risk management processes.

In this context, the course provides participants with a solid foundation in the conceptual and mathematical principles of probabilistic risk assessment, primarily addressed in Module 1, where key metrics such as the Loss Exceedance Curve (LEC), Average Annual Loss (AAL), and Probable Maximum Loss (PML) are introduced, among others, presented in Units 2 and 3. These metrics constitute fundamental inputs for financial risk evaluation and for the prioritization of risk reduction and financial protection measures.

In addition, Module 3 of the course further explores the application of these results in real-world decision-making contexts, incorporating advanced approaches such as holistic risk assessment, infrastructure system resilience modeling, robust decision-making under deep uncertainty, and risk control engineering. These contents enable participants to understand how the technical results of risk analyses can be integrated into territorial planning processes, public investment strategies, emergency management, and the design of adaptation and financial protection strategies, in alignment with the needs of the canton of Heredia and the institutional mandate of the CNE.

6.1.2 Management and Updating of the Infrastructure Exposure Database

The Strategic Project requires not only the generation of risk results, but also the strengthening of local capacities to manage, update, and expand the infrastructure exposure database, beyond the duration of the GRMA project.

This component is addressed transversally within the course, beginning in Module 1, where Unit 5 presents the methodology for constructing inventories of exposed elements, including their physical characterization, functional use, and economic value. Participants acquire technical criteria for representing exposure and for integrating it into probabilistic risk models.

Subsequently, throughout the different components of Module 2, participants learn how to link the exposure database with hazard and vulnerability models corresponding to the hazards prioritized in the Strategic Project, specifically fluvial flood, pluvial flood, and earthquakes, applied to the portfolio of buildings and infrastructure in the canton of Heredia using the specialized tools available in the CAPRA-ROBOT platform and its complementary software. This approach strengthens the capacity of technical stakeholders to update exposure information and perform spatial risk analyses independently, ensuring the sustainability of the assessments beyond the GRMA project.

Additionally, as part of the technical support process, meetings have been held with the technical working group of the canton of Heredia, aimed at explaining the methodological process followed for constructing the database of buildings and critical infrastructure, as well as the criteria used for their characterization and valuation within the probabilistic risk assessment. This support seeks to facilitate the ability of local teams to replicate and update the process autonomously in the future, beyond the scope of the project.

In this context, a technical meeting was held between the Municipality of Heredia, Ingeniar Risk-Intelligence, and CIMNE, during which the building database of the canton was reviewed in detail and questions that arose during Workshop 2 were clarified, particularly regarding building height information. During the session, it was explained that the database developed by the Municipality of Heredia is primarily designed for cadastral and tax collection purposes, describing properties based on ownership-based parcel disaggregation, which does not necessarily coincide with the unit of analysis required for probabilistic risk assessment, where the focus is on the building as the exposed element.

In this regard, the technical process required to group records corresponding to multiple parcels forming a single building was explained, as well as, in specific cases, the need to disaggregate records when a single cadastral parcel corresponds to several independent buildings. The meeting also helped clarify the conceptual and methodological difference between the cadastral database used as an input and the database of exposed elements required for risk analyses, integrating relevant physical variables such as structural type, wall materials, and building condition. It is important to highlight that much of this information is already available thanks to the solid work carried out by the Municipality of Heredia in collecting and systematizing cadastral information, which constitutes a fundamental basis for the sustainability of risk assessments.

6.1.3 Institutional Coordination and Alignment with the CNE Mandate

Capacity strengthening is not limited to the technical domain but also includes institutional coordination and the alignment of the risk assessment outputs with the needs of the entities responsible for disaster risk management in Costa Rica, particularly the National Emergency Commission (CNE).

The course is aimed at professionals associated with the Technical Working Group of the GRMA – Costa Rica program, as well as officials from other national and local institutions, promoting a common language and a shared understanding of the concepts, methods, and results of probabilistic risk assessment. Through the course content and the interaction spaces with the working group, the objective is to ensure that the results of the risk analysis are understandable, useful, and applicable to support key functions of the CNE, such as territorial planning, emergency planning, and the management of the continuity of essential services.

6.1.4 Continuity and Scalability of Risk Assessments

In line with the Terms of Reference, the capacity development process is designed to ensure that institutions such as the CNE, the Municipality of Heredia, and other national technical stakeholders are able to update and expand risk assessments in the future, including their potential scaling to the national level and to additional sectors.

The use of standardized methodologies and internationally recognized tools, such as CAPRA-ROBOT and the different hazard and vulnerability modeling modules, contributes to the technical sustainability of the assessments. Likewise, the course's emphasis on a comprehensive understanding of the risk modeling process, from data construction to the interpretation and use of results, strengthens the technical autonomy of participants and reduces dependence on external assistance in the medium and long term.

In this sense, the Course on Probabilistic Disaster Risk Modeling constitutes a fundamental pillar of the Strategic Project for the canton of Heredia, as it establishes the basis for the institutional appropriation of the results, their future updating, and their effective use in decision-making processes aimed at disaster risk reduction and climate change adaptation.

6.2 Participation Summary

The following is the list of participants who have completed Module 1 of the Course on Probabilistic Disaster Risk Modeling to date, and who reported being linked to the Strategic Project, together with the institution to which they belong. It is important to note that individuals who are part of the technical working groups are not necessarily enrolled in the course.

Table 18. Participants associated with the strategic project of Heredia.

Name	Institution	e-mail
Alonso Alvarado	Municipalidad Heredia	aalvarado@heredia.go.cr
Alonso Ulate Castillo	Laboratorio Nacional de Materiales y Modelos Estructurales, Universidad de Costa Rica	alonso.ulate@ucr.ac.cr
Bryan Rodríguez Gómez	Municipalidad Heredia	brodriguez@heredia.go.cr
Ana Cecilia Castro Chacón	Superintendencia General de Seguros	CASTROCA@Sugese.fi.cr
Sergio Alvarez González	Laboratorio Nacional de Materiales y Modelos Estructurales, Universidad de Costa Rica	sergiogabriel.alvarez@ucr.ac.cr
Karol Fallas Corrales	Municipalidad Heredia	kfallas@heredia.go.cr
Mauricio Mora	Escuela de Geología, Universidad de Costa Rica	mauricio.mora@ucr.ac.cr
Rodolfo Rothe Cordero	Municipalidad de Heredia	rrothe@heredia.go.cr

Of these participants, Alonso Ulate Castillo, Alonso Alvarado, and Ana Cecilia Castro Chacón have completed Module 2 in one of the hazards offered in the course.

6.3 Participants Feedback

To assess the knowledge acquired and the capacity development of participants, a final feedback and reflection questionnaire will be administered upon completion of Module 3 of the Probabilistic Risk Assessment course.

This instrument will collect both qualitative and quantitative information regarding learning outcomes, the level of assimilation of the technical concepts covered, and participants' perceptions of the usefulness of the tools presented—particularly CAPRA Robot.

The questionnaire includes open-ended and multiple-choice questions designed to evaluate both conceptual understanding and the practical application of course content. The questions included are as follows:

1. What key learnings did this training provide regarding probabilistic risk assessment and the use of CAPRA Robot?

Question type: Open-ended.

Objective: Identify perceived achievements and meaningful learning outcomes reported by the participant.

2. After the course, which of the following options best describes your current level of familiarity with concepts such as the Loss Exceedance Curve (LEC), Average Annual Loss (AAL), and Probable Maximum Loss (PML)?

Question type: Single-choice selection.

- I do not yet understand them.
- I partially understand them.
- I have a general understanding and know when they are applied.
- I feel comfortable using them with guidance.
- I can explain and apply them confidently.

Objective: Measure the level of understanding and technical appropriation of key risk indicators.

3. How would you now describe the main function of CAPRA Robot within the CAPRA platform?

Question type: Multiple-choice (single answer).

- Generate visual reports on social vulnerability.
- Estimate risk by calculating losses from hazards using a probabilistic approach.
- Record geographic information of exposed assets.
- Send automatic notifications during extreme events.

Correct answer: b.

Objective: Verify understanding of CAPRA Robot's technical purpose.

4. Do you consider that your skills in using risk modeling tools have improved as a result of the course? Please justify your answer.

Question type: Open-ended.

Objective: Explore the development of technical capacities resulting from the training experience.

5. Have you identified how you will apply what you have learned in your professional activities? Please describe a possible application scenario.

Question type: Open-ended

Objective: Assess the projection of learning into the participant's professional context.

6. Which of the following options best describes your current perception of the importance of tools such as CAPRA Robot for risk management?

Question type: Single-choice selection.

- Not important at all.
- Slightly important.
- Moderately important.
- Important.
- Very important.

Objective: Evaluate the participant's perception of the relevance of these tools at the end of the training.

7. Which of the following options best describes the probabilistic approach used by CAPRA Robot to calculate risk?

Question type: Multiple-choice (single answer).

- a. Uses historical data to predict future events without considering uncertainty.
- b. Calculates expected losses based on the frequency and severity of possible events, allowing estimation of the probability of exceeding certain loss levels.
- c. Applies deterministic rules based on observed damages from past events.
- d. Requires only the location of exposed assets to calculate risk.

Correct answer: b.

Evaluates: Understanding of the probabilistic model and its advantages over deterministic approaches.

8. What is the general process followed by CAPRA Robot to generate the Loss Exceedance Curve (LEC)?

Question type: Multiple-choice (single answer).

- a. Estimate population, apply damage statistics, and calculate exposure rate.
- b. Obtain insured value data, simulate historical events, and calculate damage distribution.
- c. Integrate hazard, vulnerability, and exposure data to calculate losses under multiple scenarios and derive the exceedance curve.
- d. Evaluate census quality, apply hazard maps, and plot damage curves.

Correct answer: c.

Evaluates: Understanding of the technical workflow and key model variables.

9. How does CAPRA Robot handle loss aggregation in a multi-hazard scenario, and why is this useful for risk management?

Question type: Multiple-choice (single answer).

- a. Calculates losses individually by hazard and reports only the highest to avoid duplication.
- b. Sums estimated losses for all hazards without considering correlation, resulting in more conservative scenarios.
- c. Aggregates losses considering possible interactions among hazards and allows estimation of consolidated risk, supporting more comprehensive planning.
- d. Evaluates each hazard separately and does not aggregate to avoid loss of precision.

Correct answer: c.

Evaluates: Applied understanding of the multi-hazard approach and its usefulness for decision-making.

The results of the final questionnaire will allow documentation of the impact of the capacity-building process, in line with the project's objective of equipping Lanamme and the University of Costa Rica to conduct quantitative risk analyses for road infrastructure in an autonomous and replicable manner.

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A.1 DATA FOR GENERATING THE EMPIRICAL RISK CURVES

The characteristics of the events presented herein are taken directly from the data source, and therefore, the names, categories, and other properties are presented in Spanish.

Historical losses in the infrastructure and building sectors of the canton of Heredia
Source: Ministry of National Planning and Economic Policy

Year	Type of event	Category	Subcategory	Event	Constant value in colones
1998	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	PLAN REGULADOR HURACAN MITCH	87,392,555.71
1999	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	FENOMENOS HIDROMETEOROLOGICOS PRESENTADOS ENTRE EL 12 DE AGOSTO AL 5 DE OCTUBRE DE 1999	14,101,960.98
1999	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	FENOMENOS HIDROMETEOROLOGICOS PRESENTADOS ENTRE EL 12 DE AGOSTO AL 5 DE OCTUBRE DE 1999	69,081,027.98
1999	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	FENOMENOS HIDROMETEOROLOGICOS PRESENTADOS ENTRE EL 12 DE AGOSTO AL 5 DE OCTUBRE DE 1999	119,036,681.85
2001	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	LLUVIAS SEMIPERMANENTES Y DE VARIABLE INTENSIDAD EN LA VERTIENTE CARIBE Y NORTE	559,320,453.90
2005	Hidrometeorológico	LLUVIAS INTENSAS		INUNDACIONES EN LA VERTIENTE DEL PACÍFICO Y ZONA NORTE (ONDA TROPICAL E INFLUENCIA INDIRECTA HURACÁN RITA Y VILMA)	32,863,210.73
2007	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	LLUVIAS INTENSAS ASOCIADAS AL PASO DE UNA ONDA DECRETO 33834-MP	930,261,329.68
2007	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	PLAN GENERAL DE LA EMERGENCIA POR TEMPORAL Y PASO DE UNA ONDA TROPICAL EN EL PACIFICO CENTRAL, NORTE, SUR Y CORDILLERA DE GUANACASTE, DECRETO 34045-MP	48,926,560.82
2007	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	PLAN GENERAL DE LA EMERGENCIA POR TEMPORAL Y PASO DE UNA ONDA TROPICAL EN EL PACIFICO CENTRAL, NORTE, SUR Y CORDILLERA DE GUANACASTE, DECRETO 34045-MP	1,232,030,321.21
2007	Hidrometeorológico	LLUVIAS INTENSAS	Aumento de Caudal	LLUVIAS INTENSAS ASOCIADAS AL PASO DE UNA ONDA DECRETO 33834-MP	634,449,329.70
2007	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	LLUVIAS INTENSAS ASOCIADAS AL PASO DE UNA ONDA DECRETO 33834-MP	158,612,332.43
2007	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	LLUVIAS INTENSAS ASOCIADAS AL PASO DE UNA ONDA DECRETO 33834-MP	20,619,603.22
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	95,468,865.71
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	129,199,861.74
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	163,228,887.97
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	3,930,683,703.12
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	23,629,148.56
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	47,258,297.12
2009	Geotectónico	SISMO		SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	2,029,490,609.60
2009	Geotectónico	SISMO	Movimiento de Masas	SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	233,875,680.34
2009	Geotectónico	SISMO	Movimiento de Masas	SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	1,719,788,109.94
2010	Hidrometeorológico	LLUVIAS INTENSAS		TORMENTA TROPICAL NICOLE	30,423,322.28
2010	Hidrometeorológico	LLUVIAS INTENSAS	Aumento de Caudal	TORMENTA TROPICAL NICOLE	30,423,322.28

Year	Type of event	Category	Subcategory	Event	Constant value in colones
2010	Hidrometeorológico	LLUVIAS INTENSAS	Movimiento de Masas	TORMENTA TROPICAL NICOLE	121,693,289.10
2017	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	TORMENTA TROPICAL NATE	27,504,641.41

Historic losses in the services and construction sectors nationwide

Source: Ministry of National Planning and Economic Policy

Year	Type of event	Category	Subcategory	Event	Canton	Constant value in colones
1991	Geotectónico	SISMO		TERREMOTO DE ALAJUELA	603 Buenos Aires	1,318,832,934.30
1991	Geotectónico	SISMO		TERREMOTO DE LIMON	201 Alajuela	92,544,392.39
1991	Geotectónico	SISMO		TERREMOTO DE LIMON	201 Alajuela	69,408,294.29
1991	Geotectónico	SISMO		TERREMOTO DE LIMON	701 Limón	36,157,348.60
1991	Geotectónico	SISMO		TERREMOTO DE LIMON	701 Limón	249,384,001.39
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	HURACAN CESAR	119 Perez Zeledón	141,275,487.20
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	HURACAN CESAR	607 Golfito	30,392,598.92
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN REGULADOR TORMENTA TROPICAL LILI	103 Desamparados	7,281,588.75
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	HURACAN CESAR	119 Perez Zeledón	30,392,598.87
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	HURACAN CESAR	119 Perez Zeledón	75,146,535.74
1996	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	HURACAN CESAR	605 Osa	30,392,598.92
2006	Hidrometeorológico	LLUVIAS INTENSAS			207 Palmares	76,364,895.23
2006	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	LLUVIAS INTENSAS ASOCIADAS A UN SISTEMA DE BAJA PRESION	207 Palmares	10,181,986.03
2007	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA POR TEMPORAL Y PASO DE UNA ONDA TROPICAL EN EL PACIFICO CENTRAL, NORTE, SUR Y CORDILLERA DE GUANACASTE, DECRETO 34045-MP	601 Puntarenas	26,213,411.09
2008	Hidrometeorológico	LLUVIAS INTENSAS		INUNDACIONES Y DESLIZAMIENTOS ASOCIADOS AL PASO DE LA TORMENTA TROPICAL ALMA	609 Parrita	114,045,241.75
2008	Hidrometeorológico	LLUVIAS INTENSAS		INUNDACIONES Y DESLIZAMIENTOS ASOCIADOS AL PASO DE LA TORMENTA TROPICAL ALMA	609 Parrita	35,639,138.05
2008	Hidrometeorológico	LLUVIAS INTENSAS		INUNDACIONES Y DESLIZAMIENTOS ASOCIADOS AL PASO DE LA TORMENTA TROPICAL ALMA	609 Parrita	712,782,760.92
2009	Geotectónico	SISMO		PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	402 Barva	10,154,266.23
2009	Geotectónico	SISMO		PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	402 Barva	3,275,569.75
2009	Geotectónico	SISMO		PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	404 Santa Bárbara	3,930,683.70
2009	Geotectónico	SISMO		PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	404 Santa Bárbara	2,620,455.80
2009	Geotectónico	SISMO		PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	404 Santa Bárbara	20,963,646.42

Year	Type of event	Category	Subcategory	Event	Canton	Constant value in colones
2009	Geotectónico	SISMO	Movimiento de Masas	PLAN GENERAL DE LA EMERGENCIA POR SISMO 6,2 RICHTER TERREMOTO DE CINCHONA	402 Barva	51,098,888.14
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	96,263,762.71
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	84,230,792.37
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	84,230,792.37
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	72,197,822.03
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	78,214,307.20
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	72,197,822.03
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	605 Osa	72,197,822.03
2010	Hidrometeorológico	LLUVIAS INTENSAS		TEMPORAL POR LOS EFECTOS INDIRECTOS DEL PASO DEL HURACAN TOMAS	609 Parrita	454,846,278.80
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	203 Grecia	57,594,690.66
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	142,048,443.78
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	26,965,479.74
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	7,845,559.84
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	18,275,238.38
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	2,132,221.90
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	206 Naranjo	64,134,235.50
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	211 Alfaro Ruiz	49,287,764.12
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	211 Alfaro Ruiz	2,768,975.51
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	211 Alfaro Ruiz	22,151,804.10
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	212 Sarchí	143,986,726.64
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	212 Sarchí	83,069,265.37
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	575,946.91
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	22,151,804.10
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	11,075,902.05
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	333,384,651.68
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	11,075,902.05
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	16,613,853.07
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	502 Nicoya	1,606,005,797.13
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	503 Santa Cruz	886,072,163.93

Year	Type of event	Category	Subcategory	Event	Canton	Constant value in colones
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	503 Santa Cruz	332,277,061.47
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	503 Santa Cruz	93,591,372.32
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	507 Abangares	6,645,541.23
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	507 Abangares	8,860,721.64
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	509 Nandayure	166,138,530.74
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	511 Hojanca	49,841,559.22
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	601 Puntarenas	18,829,033.48
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	601 Puntarenas	193,828,285.86
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	601 Puntarenas	49,841,559.22
2010	Geotectónico	SISMO		TERREMOTO DE SAMARA	601 Puntarenas	635,756,777.62
2015	Hidrometeorológico	LLUVIAS INTENSAS		INUNDACIONES Y DESLIZAMIENTOS PROVOCADOS POR TEMPORAL Y PASO DE UN SISTEMA DE BAJA PRESION. PROVINCIA DE LIMON Y CANTONES DE SARAPIQUI Y TURRIALBA	704 Talamanca	614,500,000.00
2015	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	INUNDACIONES Y DESLIZAMIENTOS PROVOCADOS POR TEMPORAL Y PASO DE UN SISTEMA DE BAJA PRESION. PROVINCIA DE LIMON Y CANTONES DE SARAPIQUI Y TURRIALBA	702 Pococí	12,000,000.00
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	10,554,174.58
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	3,518,058.19
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	100,515,948.36
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	154,333,316.65
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	74,806,180.12
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	1,778,923,212.85
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	20,103,189.67
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	213 Upala	153,789,401.00
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	214 Los Chiles	21,525,490.34
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	215 Guatuso	80,412,758.69

Year	Type of event	Category	Subcategory	Event	Canton	Constant value in colones
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	216 Río Cuarto	250,586,259.27
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	410 Sarapiquí	726,296,356.20
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	410 Sarapiquí	981,569,395.71
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	410 Sarapiquí	185,954,504.47
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	504 Bagaces	251,289,870.91
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	510 La Cruz	63,325,047.47
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	607 Golfito	80,412,758.69
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	702 Pococí	1,551,972,489.79
2016	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACIÓN PROVOCADA POR EL PASO DEL HURACAN OTTO POR TERRITORIO COSTARRICENSE	702 Pococí	60,309,569.02
2017	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACION PROVOCADA POR LA TORMENTA TROPICAL NATE	112 Acosta	108,053,948.39
2017	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACION PROVOCADA POR LA TORMENTA TROPICAL NATE	119 Perez Zeledón	23,084,252.61
2017	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACION PROVOCADA POR LA TORMENTA TROPICAL NATE	103 Desamparados	98,230,862.17
2017	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA ANTE LA SITUACION PROVOCADA POR LA TORMENTA TROPICAL NATE	605 Osa	117,877,034.61
2021	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA TEMPORAL EN LA VERTIENTE DEL CARIBE	305 Turrialba	69,666,927.07
2021	Hidrometeorológico	LLUVIAS INTENSAS	Inundación	PLAN GENERAL DE LA EMERGENCIA TEMPORAL EN LA VERTIENTE DEL CARIBE	701 Limón	928,892.36

A. 2 RISK ASSESSMENT DATASET FOR HEREDIA

As part of the products included in this deliverable, a web repository (Drive) was established to host the risk results for buildings and infrastructure for the Heredia project. This repository compiles deliverables .5b, 5c, 5d.

Below is a list of the files that comprise this dataset.

The link to access the dataset is:

<https://onedrive.live.com/?redeem=aHR0cHM6Ly8xZHZH2Lm1zL2YvYy85ZjZmNTQ4ZGFkMDc1MzQzLOVvTWNDRIkV3psTmdaZ0k2YTk5eWdNQlBINERfYThVTFV4QnN3Y2RFZi1ta3c%5FZT1qQ2RlZzU&id=9F6F548DAD075343%21sd9311ddf7d5e4290acdf8566692f9d81&cid=9F6F548DAD075343&sb=name&sd=1>

Landslide triggered by rain

Buildings

This directory contains the building risk result files for the canton of Heredia associated with rainfall-triggered landslide hazard.

File	Format
Heredia_desliz_lluvia_CR-SIRGAS	.shp
Heredia_desliz_lluvia_WGS84	.shp

The *.shp files used in this project are available in vector format and require a Geographic Information System (GIS) for visualization.

Infrastructure

This directory contains the infrastructure risk result files for the canton of Heredia associated with rainfall-triggered landslide hazard.

File	Format
Acueducto_Fuentes_Desliz-Lluvia_CR-SIRGAS	.shp
Acueducto_Fuentes_Desliz-Lluvia_WGS84	.shp
Acueducto_Hidrantes_Desliz-Lluvia_CR-SIRGAS	.shp
Acueducto_Hidrantes_Desliz-Lluvia_WGS84	.shp
Acueducto_Sist-Bombeo_Desliz-Lluvia_CR-SIRGAS	.shp
Acueducto_Sist-Bombeo_Desliz-Lluvia_WGS84	.shp
Acueducto_Tanques_Desliz-Lluvia_CR-SIRGAS	.shp
Acueducto_Tanques_Desliz-Lluvia_WGS84	.shp
Acueducto_Tuberias_Desliz-Lluvia_CR-SIRGAS	.shp
Acueducto_Tuberias_Desliz-Lluvia_WGS84	.shp
Alcantarillado_Colectores_Desliz-Lluvia_CR-SIRGAS	.shp
Alcantarillado_Colectores_Desliz-Lluvia_WGS84	.shp
Alcantarillado_Pozos_Desliz-Lluvia_CR-SIRGAS	.shp
Alcantarillado_Pozos_Desliz-Lluvia_WGS84	.shp

File	Format
Alcantarillado_PTAR_Desliz-Lluvia_CR-SIRGAS	.shp
Alcantarillado_PTAR_Desliz-Lluvia_WGS84	.shp
Antenas_Desliz-Lluvia_CR-SIRGAS	.shp
Antenas_Desliz-Lluvia_WGS84	.shp
Electrico_Distribucion_Circuitos_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Distribucion_Circuitos_Desliz-Lluvia_WGS84	.shp
Electrico_Distribucion_Postes_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Distribucion_Postes_Desliz-Lluvia_WGS84	.shp
Electrico_Distribucion_Transformadores_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Distribucion_Transformadores_Desliz-Lluvia_WGS84	.shp
Electrico_Generacion_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Generacion_Desliz-Lluvia_WGS84	.shp
Electrico_Transmision_Circuitos_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Transmision_Circuitos_Desliz-Lluvia_WGS84	.shp
Electrico_Transmision_Subestaciones_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Transmision_Subestaciones_Desliz-Lluvia_WGS84	.shp
Electrico_Transmision_Torres_Desliz-Lluvia_CR-SIRGAS	.shp
Electrico_Transmision_Torres_Desliz-Lluvia_WGS84	.shp
Ferreo_Desliz-Lluvia_CR-SIRGAS	.shp
Ferreo_Desliz-Lluvia_WGS84	.shp
Poliducto_Desliz-Lluvia_CR-SIRGAS	.shp
Poliducto_Desliz-Lluvia_WGS84	.shp
Puentes_Desliz-Lluvia_CR-SIRGAS	.shp
Puentes_Desliz-Lluvia_WGS84	.shp
Vias_Desliz-Lluvia_CR-SIRGAS	.shp
Vias_Desliz-Lluvia_WGS84	.shp

Landslide triggered by earthquake

Buildings

This directory contains the building risk result files for the canton of Heredia associated with earthquake-triggered landslide hazard.

File	Format
Heredia_desliza_sismo_CR-SIRGAS	.shp
Heredia_desliza_sismo_WGS84	.shp

Infrastructure

This directory contains the infrastructure risk result files for the canton of Heredia associated with earthquake-triggered landslide hazard.

File	Format
Acueducto_Fuentes_Desliz-Sismo_CR-SIRGAS	.shp
Acueducto_Fuentes_Desliz-Sismo_WGS84	.shp

File	Format
Acueducto_Hidrantes_Desliz-Sismo_CR-SIRGAS	.shp
Acueducto_Hidrantes_Desliz-Sismo_WGS84	.shp
Acueducto_Sist-Bombeo_Desliz-Sismo_CR-SIRGAS	.shp
Acueducto_Sist-Bombeo_Desliz-Sismo_WGS84	.shp
Acueducto_Tanques_Desliz-Sismo_CR-SIRGAS	.shp
Acueducto_Tanques_Desliz-Sismo_WGS84	.shp
Acueducto_Tuberias_Desliz-Sismo_CR-SIRGAS	.shp
Acueducto_Tuberias_Desliz-Sismo_WGS84	.shp
Alcantarillado_Coletores_Desliz-Sismo_CR-SIRGAS	.shp
Alcantarillado_Coletores_Desliz-Sismo_WGS84	.shp
Alcantarillado_Pozos_Desliz-Sismo_CR-SIRGAS	.shp
Alcantarillado_Pozos_Desliz-Sismo_WGS84	.shp
Alcantarillado_PTAR_Desliz-Sismo_CR-SIRGAS	.shp
Alcantarillado_PTAR_Desliz-Sismo_WGS84	.shp
Antenas_Desliz-Sismo_CR-SIRGAS	.shp
Antenas_Desliz-Sismo_WGS84	.shp
Electrico_Distribucion_Circuitos_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Circuitos_Desliz-Sismo_WGS84	.shp
Electrico_Distribucion_Postes_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Postes_Desliz-Sismo_WGS84	.shp
Electrico_Distribucion_Transformadores_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Transformadores_Desliz-Sismo_WGS84	.shp
Electrico_Generacion_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Generacion_Desliz-Sismo_WGS84	.shp
Electrico_Transmision_Circuitos_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Circuitos_Desliz-Sismo_WGS84	.shp
Electrico_Transmision_Subestaciones_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Subestaciones_Desliz-Sismo_WGS84	.shp
Electrico_Transmision_Torres_Desliz-Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Torres_Desliz-Sismo_WGS84	.shp
Ferreo_Desliz-Sismo_CR-SIRGAS	.shp
Ferreo_Desliz-Sismo_WGS84	.shp
Poliducto_Desliz-Sismo_CR-SIRGAS	.shp
Poliducto_Desliz-Sismo_WGS84	.shp
Puentes_Desliz-Sismo_CR-SIRGAS	.shp
Puentes_Desliz-Sismo_WGS84	.shp
Vias_Desliz-Sismo_CR-SIRGAS	.shp
Vias_Desliz-Sismo_WGS84	.shp

Fluvial Flood

Buildings

This directory contains the building risk result files for the canton of Heredia associated with fluvial flooding hazard.

File	Format
Heredia_inunda_fluvial_CR-SIRGAS	.shp

Heredia_inunda_fluvial_WGS84	.shp
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Infrastructure

This directory contains the infrastructure risk result files for the canton of Heredia associated with fluvial flooding hazard.

File	Format
Acueducto_Fuentes_Fluvial_CR-SIRGAS	.shp
Acueducto_Fuentes_Fluvial_WGS84	.shp
Acueducto_Sist-Bombeo_Fluvial_CR-SIRGAS	.shp
Acueducto_Sist-Bombeo_Fluvial_WGS84	.shp
Alcantarillado_PTAR_Fluvial_CR-SIRGAS	.shp
Alcantarillado_PTAR_Fluvial_WGS84	.shp
Antenas_Fluvial_CR-SIRGAS	.shp
Antenas_Fluvial_WGS84	.shp
Electrico_Distribucion_Transformadores_Fluvial_CR-SIRGAS	.shp
Electrico_Distribucion_Transformadores_Fluvial_WGS84	.shp
Electrico_Generacion_Fluvial_CR-SIRGAS	.shp
Electrico_Generacion_Fluvial_WGS84	.shp
Electrico_Transmision_Subestaciones_Fluvial_CR-SIRGAS	.shp
Electrico_Transmision_Subestaciones_Fluvial_WGS84	.shp
Ferreo_Fluvial_CR-SIRGAS	.shp
Ferreo_Fluvial_WGS84	.shp
Puentes_Fluvial_CR-SIRGAS	.shp
Puentes_Fluvial_WGS84	.shp
Vias_Fluvial_CR-SIRGAS	.shp
Vias_Fluvial_WGS84	.shp

Pluvial Flood

Buildings

This directory contains the building risk result files for the canton of Heredia associated with pluvial flooding hazard.

File	Format
Heredia_inunda_pluvial_CR-SIRGAS	.shp
Heredia_inunda_pluvial_WGS84	.shp

Infrastructure

This directory contains the infrastructure risk result files for the canton of Heredia associated with pluvial flooding hazard.

File	Format
Acueducto_Fuentes_Pluvial_CR-SIRGAS	.shp
Acueducto_Fuentes_Pluvial_WGS84	.shp
Acueducto_Sist-Bombeo_Pluvial_CR-SIRGAS	.shp
Acueducto_Sist-Bombeo_Pluvial_WGS84	.shp
Alcantarillado_PTAR_Pluvial_CR-SIRGAS	.shp
Alcantarillado_PTAR_Pluvial_WGS84	.shp
Antenas_Pluvial_CR-SIRGAS	.shp
Antenas_Pluvial_WGS84	.shp
Electrico_Distribucion_Transformadores_Pluvial_CR-SIRGAS	.shp
Electrico_Distribucion_Transformadores_Pluvial_WGS84	.shp
Electrico_Generacion_Pluvial_CR-SIRGAS	.shp
Electrico_Generacion_Pluvial_WGS84	.shp
Electrico_Transmision_Subestaciones_Pluvial_CR-SIRGAS	.shp
Electrico_Transmision_Subestaciones_Pluvial_WGS84	.shp
Ferreo_Pluvial_CR-SIRGAS	.shp
Ferreo_Pluvial_WGS84	.shp
Puentes_Pluvial_CR-SIRGAS	.shp
Puentes_Pluvial_WGS84	.shp
Vias_Pluvial_CR-SIRGAS	.shp
Vias_Pluvial_WGS84	.shp

Earthquake

Buildings

This directory contains the building risk result files for the canton of Heredia associated with earthquake hazard.

File	Format
Heredia_sismo_CR-SIRGAS	.shp
Heredia_sismo_WGS84	.shp

Infrastructure

This directory contains the infrastructure risk result files for the canton of Heredia associated with earthquake hazard.

File	Format
Acueducto_Fuentes_Sismo_CR-SIRGAS	.shp
Acueducto_Fuentes_Sismo_WGS84	.shp
Acueducto_Hidrantes_Sismo_CR-SIRGAS	.shp
Acueducto_Hidrantes_Sismo_WGS84	.shp
Acueducto_Sist-Bombeo_Sismo_CR-SIRGAS	.shp
Acueducto_Sist-Bombeo_Sismo_WGS84	.shp
Acueducto_Tanques_Sismo_CR-SIRGAS	.shp
Acueducto_Tanques_Sismo_WGS84	.shp

File	Format
Acueducto_Tuberias_Sismo_CR-SIRGAS	.shp
Acueducto_Tuberias_Sismo_WGS84	.shp
Alcantarillado_Coletores_Sismo_CR-SIRGAS	.shp
Alcantarillado_Coletores_Sismo_WGS84	.shp
Alcantarillado_Pozos_Sismo_CR-SIRGAS	.shp
Alcantarillado_Pozos_Sismo_WGS84	.shp
Alcantarillado_PTAR_Sismo_CR-SIRGAS	.shp
Alcantarillado_PTAR_Sismo_WGS84	.shp
Antenas_Sismo_CR-SIRGAS	.shp
Antenas_Sismo_WGS84	.shp
Electrico_Distribucion_Circuitos_Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Circuitos_Sismo_WGS84	.shp
Electrico_Distribucion_Postes_Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Postes_Sismo_WGS84	.shp
Electrico_Distribucion_Transformadores_Sismo_CR-SIRGAS	.shp
Electrico_Distribucion_Transformadores_Sismo_WGS84	.shp
Electrico_Generacion_Sismo_CR-SIRGAS	.shp
Electrico_Generacion_Sismo_WGS84	.shp
Electrico_Transmision_Circuitos_Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Circuitos_Sismo_WGS84	.shp
Electrico_Transmision_Subestaciones_Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Subestaciones_Sismo_WGS84	.shp
Electrico_Transmision_Torres_Sismo_CR-SIRGAS	.shp
Electrico_Transmision_Torres_Sismo_WGS84	.shp
Ferreo_Sismo_CR-SIRGAS	.shp
Ferreo_Sismo_WGS84	.shp
Poliducto_Sismo_CR-SIRGAS	.shp
Poliducto_Sismo_WGS84	.shp
Puentes_Sismo_CR-SIRGAS	.shp
Puentes_Sismo_WGS84	.shp
Vias_Sismo_CR-SIRGAS	.shp
Vias_Sismo_WGS84	.shp

RDLS Metadata

This directory contains the metadata following the Risk Data Library Standard, providing structured information to describe, organize, and ensure the consistency of the datasets used in the project.

File	Format
Loss_Heredia_Buildings	.json

The *.json file may contain information related to hazard, exposure, vulnerability, or loss, depending on the type of data being represented within the project.